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RPI TECHNICAL REPORT MP-83

AN AUTONOMOUS ROVING VEHICLE FOR THE PLANET MARS

—

A SUMMARY OF OVER 15 YEARS OF RESEARCH

by

Dean K. Frederick

Contract MDA-903-82-K-0168

School of Engineering
Rensselaer Polytechnic Institute
Troy, New York 12180-3590

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October 1984

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ACKNOWLEDGEMENT

A project of this scope, running for many years, requires contributions from very many people and organizations. Most of the actual work was done by students, typically undergraduates, and often working on the project for three or four terms or more before graduation. Since they usually worked on specifically defined problems, there was need for those majoring in Electrical, Mechanical, Aeronautical, Materials, and Computer and Systems Engineering, as well as some in Computer Science. Just among the electrical engineers, there were students needed with some interest in motor drives, control systems, digital hardware, electro-optics, communications systems, and analog circuits. The better undergraduates on the project were chosen to participate as graduate students, almost entirely at the masters level. Their work here was usually of wider scope and they often had some management responsibilities with undergraduates in their area. Most of these rose to the occasion and many produced documents worthy of being included in our Techncial Report series. They all deserve thanks.

Quite a few faculty members have participated also over the years. The names that come to mind are Dr. George Sandor, Dr. Edward Smith, Dr. C. N. Shen, and Dr. Peter Lashmet. Particular thanks are due to Dr. David Gisser who has directed the project since September 1980 and who assisted in the preparation of this report.

However, the one who conceived the project and became the real spark-plug and the manager for most of the years was Dr. Stephen Yerazunis, who is an enthusiastic participant even today despite his physical handicaps.

Many thanks are also due to the organizations that supported the work with funds, technical advice, and interest, This support has come from the National Aeronautics and Space Administration (Grant NSG-7369), the Jet Propulsion Laboratory (Contract 954880), and the Defense Advanced Research Projects Agency

(contract MDA 903-82-K-0168). Rensselaer deserves special mention for carrying us through when times were lean.

ABSTRACT

A vehicle intended for use on Mars, and therefore capable of autonomous operation over very rough terrain, has been under development at Rensselaer Polytechnic Institute since 1967. This report is an overview of the project, including a brief summary of the early work, a somewhat longer review of the developments during 1975 to 1978, and a more detailed discussion of the test results and work done since 1979.

The early efforts were directed chiefly toward deployment, structural, and suspension problems, and resulted in a storage-battery-powered vehicle that served as a test bed for later developments. The next phase involved the development of a primitive vision system for detecting obstacles. This consisted of a pulsed laser source and single photodetector both mounted on the same mast. As the mast is rotated, they scan the terrain ahead at fixed elevation angles such that a ground reflection should be received for relatively flat terrain. Azimuth angles for which no ground reflection is received are presumed to contain boulders or craters. This information is processed and used to guide the vehicle by means of telemetry and a remote computer. Results of extensive testing of this vehicle are summarized.

A more sophisticated vision system was subsequently developed that continues to use triangulation as a basic feature, but scans the terrain ahead in two dimensions. The improved telemetry system and other hardware and software improvements are discussed, along with some fixed-position test results for this vision system. Some suggestions for the direction of future efforts are included. Problems that were not addressed in this work are obstacle avoidance and navigation for distances over three meters, and autonomous power sources suitable for extended travel.

I. INTRODUCTION

This introductory chapter will present the rationale for the study, a brief review of the 17-year history of the project, and an outline of the remaining chapters.

A. Project Rationale

Much knowledge regarding several of the solar system planets has been gained through missions employing remote sensors and more can be obtained in the future in this manner. However, many of the critical scientific questions require detailed surface experiments and measurements such as those conducted by the Viking landers on Mars. Despite the historic achievement represented by the soft landings of the Vikings and the effectiveness of the on-board experimental systems, new important questions were raised. For these to be answered, an extensive surface exploration must be undertaken. This exploration could be focused on in situ experimentation such as that involved in the Viking mission or on samples returned to Earth for analysis or possibly a combination of both. In any event, a surface trajectory involving hundreds of kilometers, and desirably over 1,000 kilometers, would be required to explore a sufficient number of the science sites to gain an adequate coverage of the planet.

The round-trip communications delay time, which ranges from a minimum of nine minutes to a maximum of 40 minutes, the limited windows during which information can be transmitted, and the relatively low data rates attainable at these distances exclude direct control of the rover from Earth as a routine matter. In addition, the value of the mission in terms of scientific knowledge gained will depend, in part, on how many sites can be visited, on how complete a coverage of the planet these sites represent, and on how much time is made available for

scientific experimentation as opposed to traversing between sites. In turn, these factors are dependent on the mobility of the rover and the strategy employed to guide the rover. The mobility of the rover, i.e., its ability to deal with in-path and cross-path slopes and with boulders and craters, and with combinations of these, determines the number of safe paths available to the desired locations. A rover characterized by low mobility will at the least have to follow an unnecessarily tortuous path, and therefore consume mission time at the expense of science time, and at the worst would be unable to reach the desired sites. On the other hand, a rover with high mobility will be able to take advantage of shorter, more direct routes and will be able to reach sites characterized by more adverse approach terrains than would be possible otherwise.

The strategy employed to guide a rover will have similar impacts. It is crucial that an overall strategy minimizing the length of the path be employed to maximize the time available for science and extend the range of the exploration of the planet. Because of the communications link restrictions referred to earlier, it would appear that a strategy which relies minimally on direct earth intervention should be implemented.

The planning of the path in terms of scale and detail should be consistent with the information to be made available by the sensors employed and would logically be implemented on several levels. Images of the planetary surface obtained from an orbiter with a 100-200 meter resolution could be employed to define an optimal path avoiding "macro" hazards. At the next level, as suggested by the Mars Science Working Group [1], photographs of the scene taken by the cameras on the rover and transmitted to Earth could be used as the basis of planning a 0.5-1.0 km path depending on the terrain situation and the scale of detail provided by the images. Below this level, sensing, interpretation and decision making would have to reside with the rover. Path lengths of the order of 40-100

meters could be based on the on-board interpretation of video images [1] and/or range and pointing-angle data [2]. Finally, a short-range system could be used for the detection and avoidance of hazards from 0.5 to 3.0 meters in front of the vehicle that would have been overlooked in the longer-range path planning.

Since 1967 many facets of the problems associated with a vehicle capable of roving the surface of Mars have been studied theoretically and experimentally at Rensselaer. In this report the work accomplished during the calendar years 1979 and 1980 is summarized. Because the details of this work have been presented in a series of previously-issued technical reports the objective of this document is to highlight the individual areas and to provide an integrated setting in which they can be viewed. Next we present a brief history of the project, with the emphasis placed on the work of the period 1975-1978.

B. Historical Review

In the early stages of the project the majority of activity was devoted to the mechanical design of the vehicle, including such features as suspension, steering, propulsion, and payload. Other areas of study included automated chemical analysis of soil samples and strategies for maneuvering around obstacles whose dimensions were large compared with those of the vehicle.

One of the early designs resembled a dragster with light, unpowered front wheels and most of the weight over the rear drive wheels. A small model, built and tested in 1970, received power and instructions through an umbilical cord. A stabilizer wheel in the rear kept the vehicle steady when its front wheels encountered obstacles, at which time the rear wheels could pull the vehicle back so an alternate path could be taken. In essence, the front wheels served as a mechanical obstacle detector, in the absence of anything more sophisticated. Another feature was a movable frame on which the motors were mounted. This frame could

be tilted in order to change the vehicle's center of gravity, thereby placing more weight on the rear wheels (for greater traction) or more weight on the front wheels (for greater stability).

During the early 1970's efforts focused on building a fully operational half-scale rover that was capable of being folded to fit inside a landing capsule. Commands from a remote-control station could initiate a series of steps in which various motors moved the wheels into position, latched the connecting struts, and finally lifted the payload box into position. Once the rover had unfolded itself, it could move and turn in response to commands from a remote-control box. An electric motor at each wheel received power from car batteries that were stored in the payload box. Wheel speeds were measured by tachometers attached to each motor, and steering was accomplished by an analog electrical system that varied the motor speeds appropriately. Testing of this model began in 1974 but control was always by an individual through the remote-control station. During this period considerable effort had been devoted to the design of an obstacle detection system. After a number of unsuccessful attempts it was determined that a system that used a pulsed laser and a photodiode detector would be feasible. To assist in the development of computer algorithms for the processing of the laser data to yield an obstacle-avoidance and path-selection system, work began on a set of computer programs that would simulate the rover passing through terrain that could range from perfectly flat to bumpy and hazardous. These efforts culminated in a completely autonomous vehicle that was tested extensively both indoors and outdoors during 1978.

During this period a variety of additional topics related to an eventual Mars mission were studied and reported. These include:

- on-line atmospheric parameter updating during landing trajectories,
- adaptive trajectory control using variable thrust and/or drag processes in concert with atmospheric parameter updating,
- feasibility of autogyro concepts for landing as opposed to retro-rocketry,
- global navigation concepts for the location of the rover,
- a non-linear optimization computer program for guidance in the design of an overall unmanned mission, and
- optimization of gas chromatographic separation systems.

C. Outline of Report

The characteristics of the vehicle that was successfully tested in 1978 are summarized in the following chapter. In Chapter III the features of the new vehicle that employs a far more sophisticated obstacle detection system than its predecessor are presented. Chapter IV contains descriptions of the various subsystems comprising the advanced obstacle detection system, and the results of some recent laboratory experiments. The report concludes with Chapter V in which plans for future work are presented.

II. THE SINGLE-LASER/SINGLE-DETECTOR OBSTACLE DETECTION SYSTEM

In this chapter a brief description of the vehicle that was tested during 1978 will be presented. Then the results of the indoor and outdoor tests will be summarized. Report MP-61 [3] can be consulted for a more detailed description.

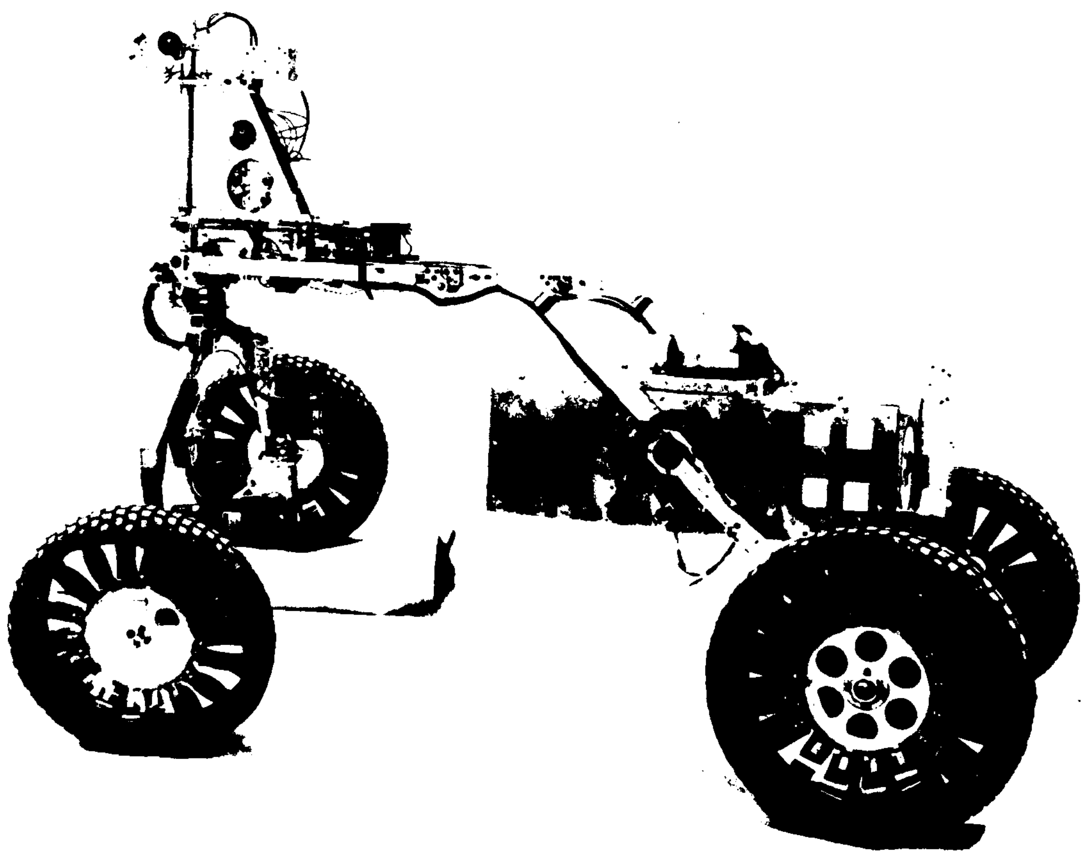
A. Vehicle Description

The vehicle and obstacle detection system that evolved from the studies during the first half of the 1970s is shown in Figure 1 and its principal components are identified in Figures 2 and 3. Several of the physical parameters are presented in Table 1.

TABLE 1. Vehicle Parameters

Height:	2.0 meters		
Length:	1.75 meters		
Weight:	front wheels		150 lbs.
	rear wheels		190 lbs.
Drive Motors:		front	2 at 1/6 HP (DC)
		rear	2 at 1/8 HP (DC)
Power Supply:		three	12-volt automobile batteries

Over the years this vehicle has served two main functions. First, it has served as a means for testing design innovations and refinements of components such as its wheels and steering mechanism. Second, the vehicle has served ably as a dynamic test bed for the obstacle detection system and should be able to perform



RENSSELAER AUTONOMOUS ROVING VEHICLE

Figure 1.

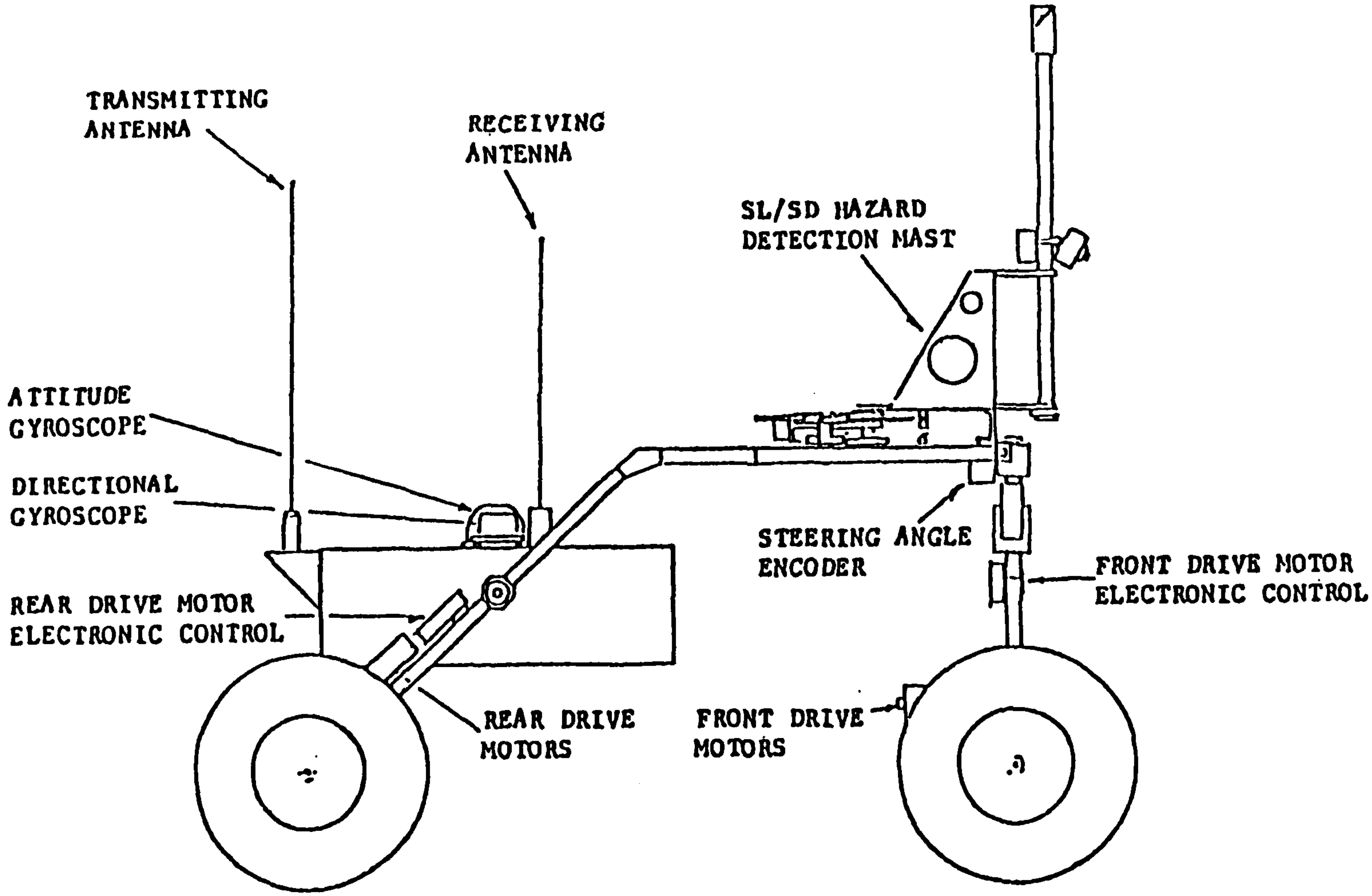


Figure 2. Vehicle with major components identified

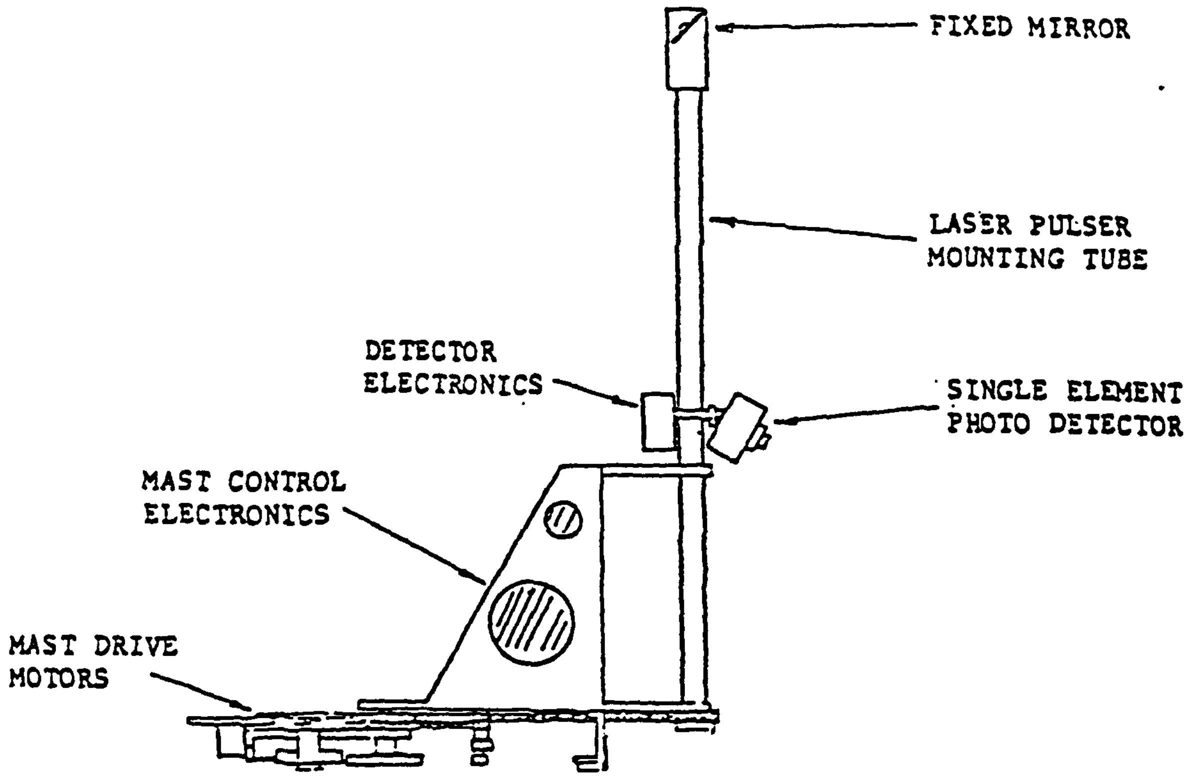


Figure 3. Mast with major components identified

this function for the advanced system that is presently under development.

Recently the question of the optimum mechanical design of a vehicle to serve specifically as a test bed was investigated [4] and the principal conclusion is that the type of suspension and steering arrangement of the present vehicle are most appropriate. One important refinement that was incorporated in the latter stages of its development is the high clearance of the front portion of the frame that supports the mast. Because the front axle can rotate through a $\pm 90^{\circ}$ angle, it is essential that there be clearance for the front wheels to fit under the chassis. This requirement is particularly critical when the vehicle is on a cross slope and undergoing a considerable amount of flexing.

B. Obstacle Detection System

The obstacle detection mast seen in Figure 3 utilized a single pulsed laser, a stationary mirror, and a single photodetector and is referred to as the single laser/single detector (SL/SD) system. These components were mounted on a tube that oscillated continuouly through $\pm 84^{\circ}$ in azimuth. A pulse of laser light was fired vertically at the mirror at 15 different azimuth angles spaced 12° apart. The angle of the mirror was set such that when the vehicle was on level terrain the laser pulse would hit the ground approximately 1.75 meters in front of it. The detector, having a narrow cone of vision, was focused on that point, as indicated in part a of Figure 4. Therefore, if at any given azimuth the pulse of laser light was picked up by the detector the terrain was considered sufficiently flat to be passable for that azimuth. If the terrain fell away due to a crater, as shown in part b of the figure, no return would be received. The geometry of the system was fixed such that an obstacle 0 25 meters or higher at a distance of 1.5 meters in front of the vehicle would also result in no return (see part c of Figure 4).

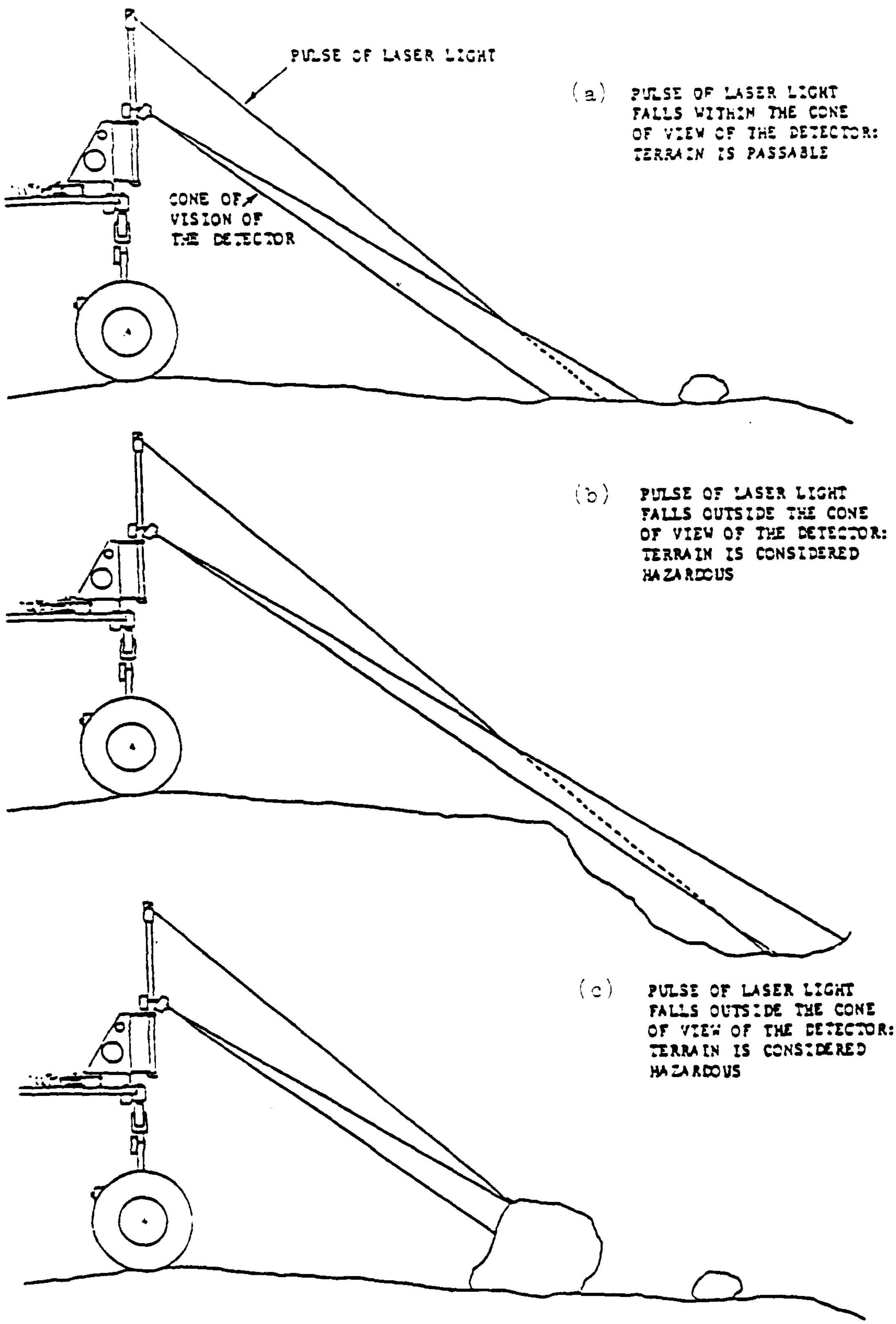


Figure 4. How the SL/SD vision system works

The tube on which the laser, mirror, and detector were mounted oscillated at a frequency of 2 Hz. With one laser pulse at each azimuth angle and 30 azimuths per oscillation, the SL/SD obstacle detection system generated information about the terrain at a rate of 30 bits per second. This information was transmitted to a remote computer via a cable for the indoor testing and via a radio link for outdoor runs.

In the computer the laser return data was processed each 0.5 second to yield a mathematical terrain model consisting of an array of either set or cleared bits. This terrain model formed the input to the path-selection algorithm (PSA) that generated the new steering commands to be transmitted back to the vehicle. The central concept of the software was embodied in a subroutine named TRKTRN (Track and Turn) in which the most recent terrain scan was examined to determine the existence of an obstacle(s). These data were used in combination with the locations of previously detected obstacles, if any, to determine if safe paths towards the desired destination existed. The availability of safe paths was based on an analysis of constraint vectors describing limiting steering actions due to the existence of new obstacles (as disclosed by the most recent scan) or old obstacles which had been detected by an earlier scan. The limiting steering actions used to calculate the constraint factors took into account the rover's dynamical characteristics from both a front- and rear-wheel point of view as well as its mobility capabilities. The logic used to implement TRKTRN on the Varian 620i minicomputer is decribed in Section III A of Report MP-61 [3].

C. Testing

The first testing of the complete SL/SD autonomous vehicle was performed during the spring and summer of 1977 and was described in Report MP-54 [5]. Both

indoor and outdoor runs were made, generally on isolated obstacles, and the system's behavior agreed quite well with the predictions of the computer simulation studies. Generally, the performance was good, with the major shortcomings being:

- the rear wheels often hit the edges of obstacles after the front wheels had cleared,
- for proper performance it was necessary to restrict the pitch and roll angles to about ± 10 degrees, and
- the path-selection system tended to make conservative decisions that resulted in longer-than-necessary paths or safe directions being classified as unsafe.

Subsequently, extensive modifications were made in the path-selection algorithm, resulting in the TRKTRN subroutine referred to above and described in Reference 3. The autonomous vehicle, with its improved PSA and numerous other refinements in both its electronic and mechanical components, was tested extensively during the summer and fall of 1978. The summer testing was done indoors in the Jonsson Engineering Center, using a variety of multiple-obstacle encounters. The outdoor testing was done on a specially tailored area whose obstacles and contours are shown in Figure 5.

These tests were documented on 16 mm film, portions of which appear in the video tape and film "Toward Manned Exploration of the Planets" [6]. The results were very favorable and are summarized in Report MP-61 [3]. The major conclusion stated is that with suitable modifications the PSA used would provide the basis for developing the multi-laser/multi-detector (ML/MD) system that was under development at that time.

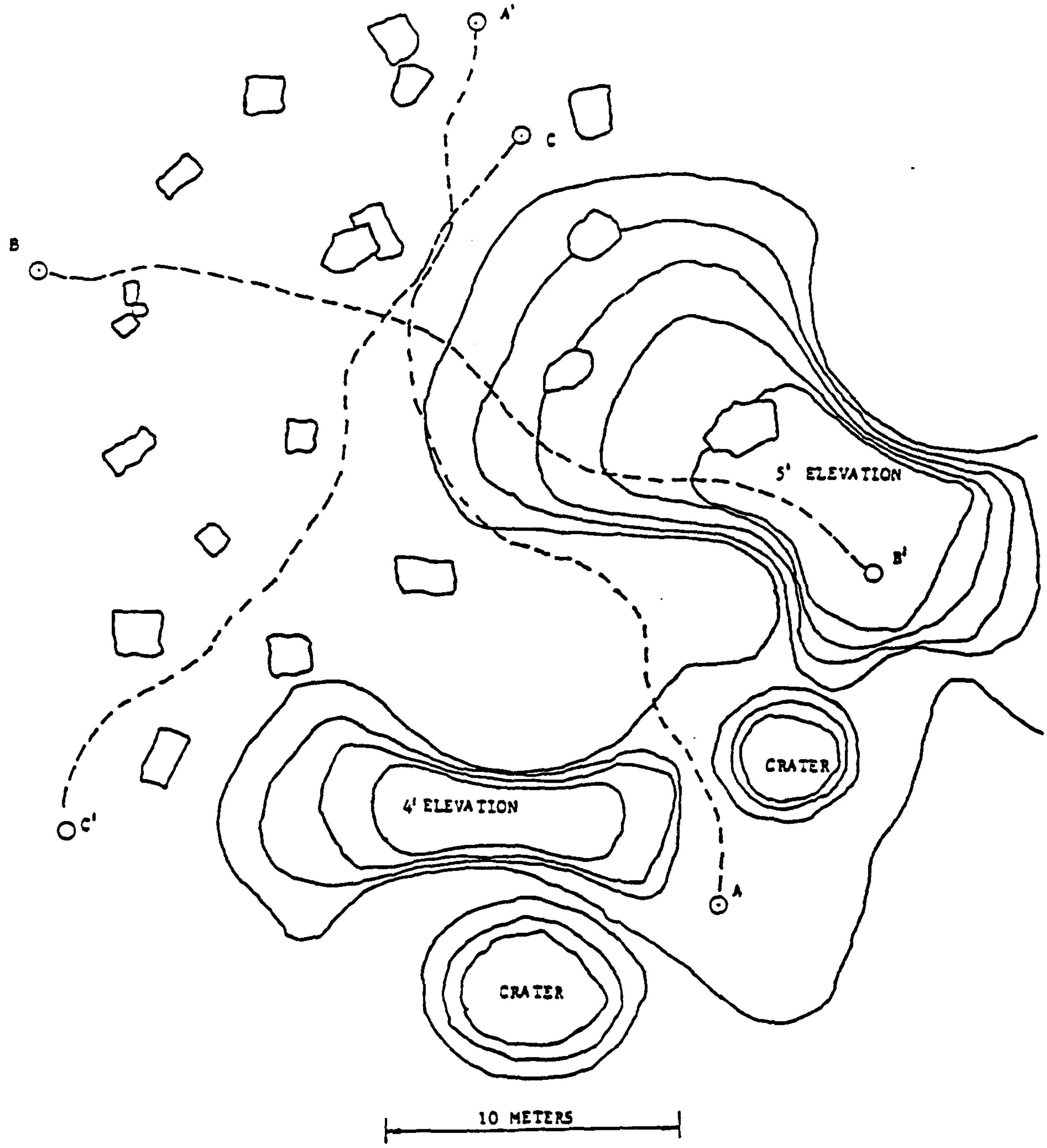


Figure 5. Rover runs on the Rensselaer test field

Based on the results of the 1978 testing and the analytical and computer simulation studies that had been performed to date, work began in earnest on the implementation of the ML/MD system. The early work in this area is summarized in Report MP-63 [7].

III. OVERVIEW OF THE MULTI-LASER/MULTI-DETECTOR SYSTEM

Much was learned from the field experience with the single-laser/single-detector system (SL/SD), and the results were sometimes impressive. However, it became clear that the higher-level terrain sensing system that had been under consideration should be implemented, particularly if the rover was to perform satisfactorily in the real pitch and roll situations that it would doubtless encounter on Mars.

In this chapter we review the concept of the multi-laser/multi-detector (ML/MD) system and identify the main system components. More detailed descriptions of the individual components will be given in the following chapter.

A. Obstacle Detection Concept

This higher-level obstacle detection system continues to use the concept of laser triangulation that formed the basis of the SL/SD system. However, the new system is capable of firing the laser at various values of elevation angle, and the detector is capable of looking for laser returns through a number of angular cones. Triangulation still occurs within the plane that contains the mast and the path of the laser pulse, and this plane rotates in azimuth about the mast axis, as before. However, the new system, called the "multi-laser/multi-detector" (ML/MD) or "elevation scanning" system is capable of placing up to 1024 points of laser light on the terrain with each azimuth scan as compared to 15 points in the former system.

Craig, in Report MP-59 [8], had presented the details of the subsystems comprising the mast and the supporting analysis. Maroon and Troiani, in Report MP-57 [9], had developed the first versions of a terrain modeler that could translate the data returned by the sensors into meaningful terrain information that could be understood by the path-selection algorithm.

The geometry associated with a hypothetical two-laser/two-detector system is depicted in Figure 6. We see that the path of laser lintersects the two detector cones along the lines labeled "a" and "b", whereas the path of laser 2 has intersection lines labeled "c" and "d". Hence, a total of four line segments having known positions relative to the vehicle are available for locating the terrain surface. For example, having returns on detector 1for laser land on detector 2 for laser 2 indicates that the terrain surface passes through line segments "a" and "d", although we do not know precisely where the terrain intersects these two lines. But, by having many lasers and many detectors and by restricting the field of view we can make the line segments be sufficiently short that a reasonably accurate image of the terrain is developed along an azimuth direction. By repeating this process at a sufficiently dense set of azimuths, we hope to generate the information required by the PSA for reliable determination of vehicle heading, even in the presence of large in-path and cross-path slopes.

A somewhat more realistic demonstration of the geometric relationships is depicted in Figure 7 for 15 lasers and 20 detectors. The 12 short heavy lines are the laser-detector cone intersections that correspond to the detector signals that will be received for the particular terrain shown.

The ML/MD system has a mast that rotates continually instead of oscillating and uses slip rings to transfer data and power between it and the body of the vehicle. To achieve the effect of many laser pulses traveling at different pointing angles, the new system uses a single solid state pulsed laser whose light is reflected by a rotating 8-sided mirror located at the top of the mast. By synchronizing the firing of the laser with the mirror position, the laser can be pointed at any desired angle within a 90^{o} field. A laser is used that has a capability of a 10 Khz firing rate, compared with a 1 Khz maximum for the SL/SD system. Rates of this order are dictated by geometry and desired system performance. Also, the new system

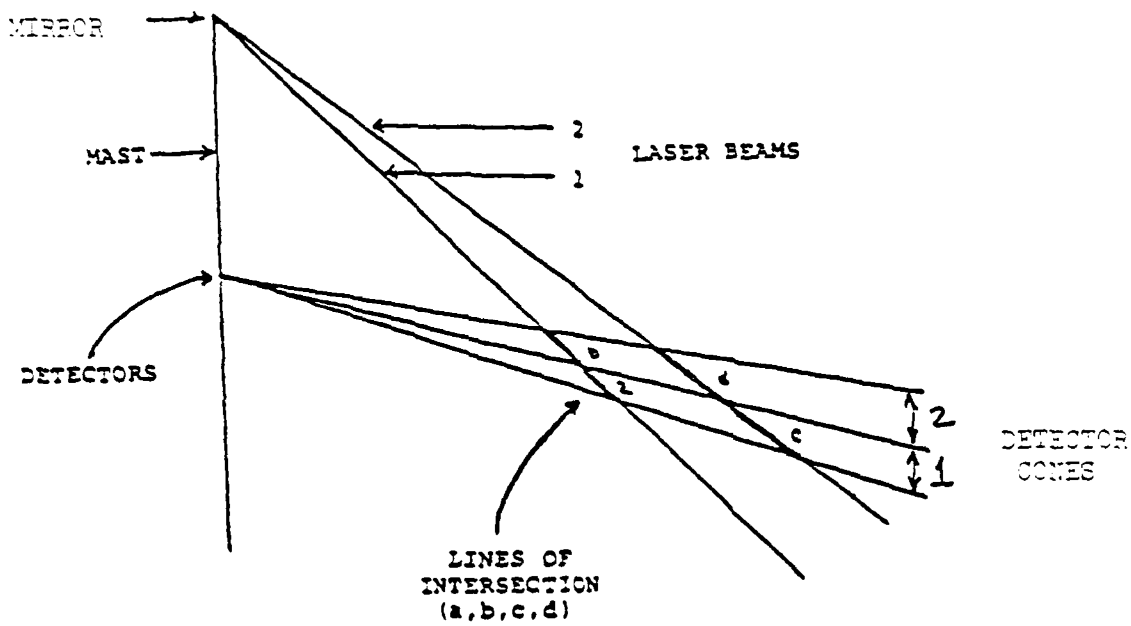


Figure 6. Geometry for a Two-Laser/Two-Detector System

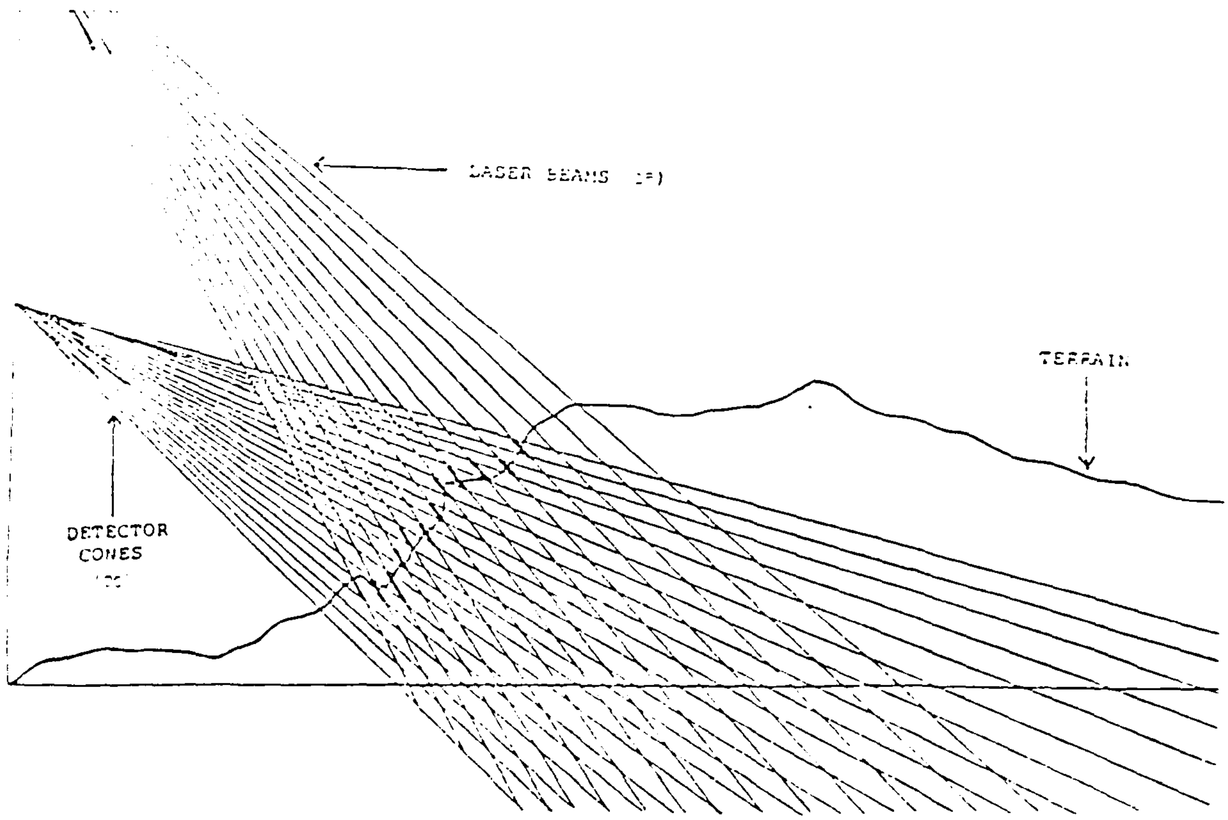


Figure 7. Geometry for a 15-laser/20-detector system

uses a multi-element detector to achieve multiple vision cones. Presently a 20-element photodiode array is being used. With this system, the approximate height of the terrain relative to the vehicle can be computed for up to 1024 points in front of the vehicle on each revolution of the mast. Figure 8 is a photograph of the mass assembly and Figure 9 indicates the location and function of the various elements comprising it.

B. System Description

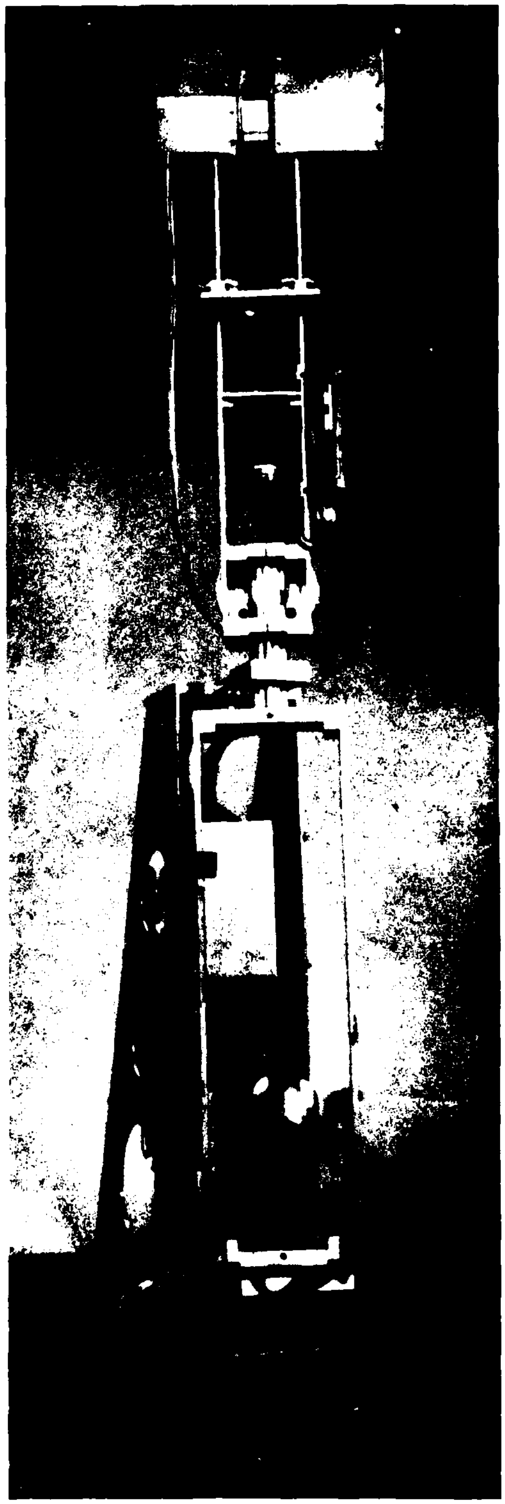
A diagram that shows the elements comprising the ML/MD system and the flow of signals between them is presented in Figure 10. Although the names of the individual blocks are the same as those for the SL/SD system, the functions of these blocks and the rates at which they must handle data are vastly different.

In Figure 11 the complete electronic system of the new-generation vehicle is shown, along with the equipment to which it is interfaced: the Prime computer, two computer terminals, and the portable command box. The types of signals present at various points are displayed also. In the following paragraphs we give an overview of the electronics system that should aid the reader in understanding the relationships between the subsystems described in Chapter IV.

C. Overview of Electronics Systems

The autonomous roving vehicle is controlled through the use of on-board electronic systems and an external, stationary computer. The block diagram of the elements for controlling the rover and gathering data from it is shown in Figure 11. The key elements are the laser mast, telemetry system, microprocessor, command link, and the Prime computer.

The laser mast provides the means by which the Rover can detect objects



ELEVATION SCANNING MAST - FRONT VIEW

Figure 8.

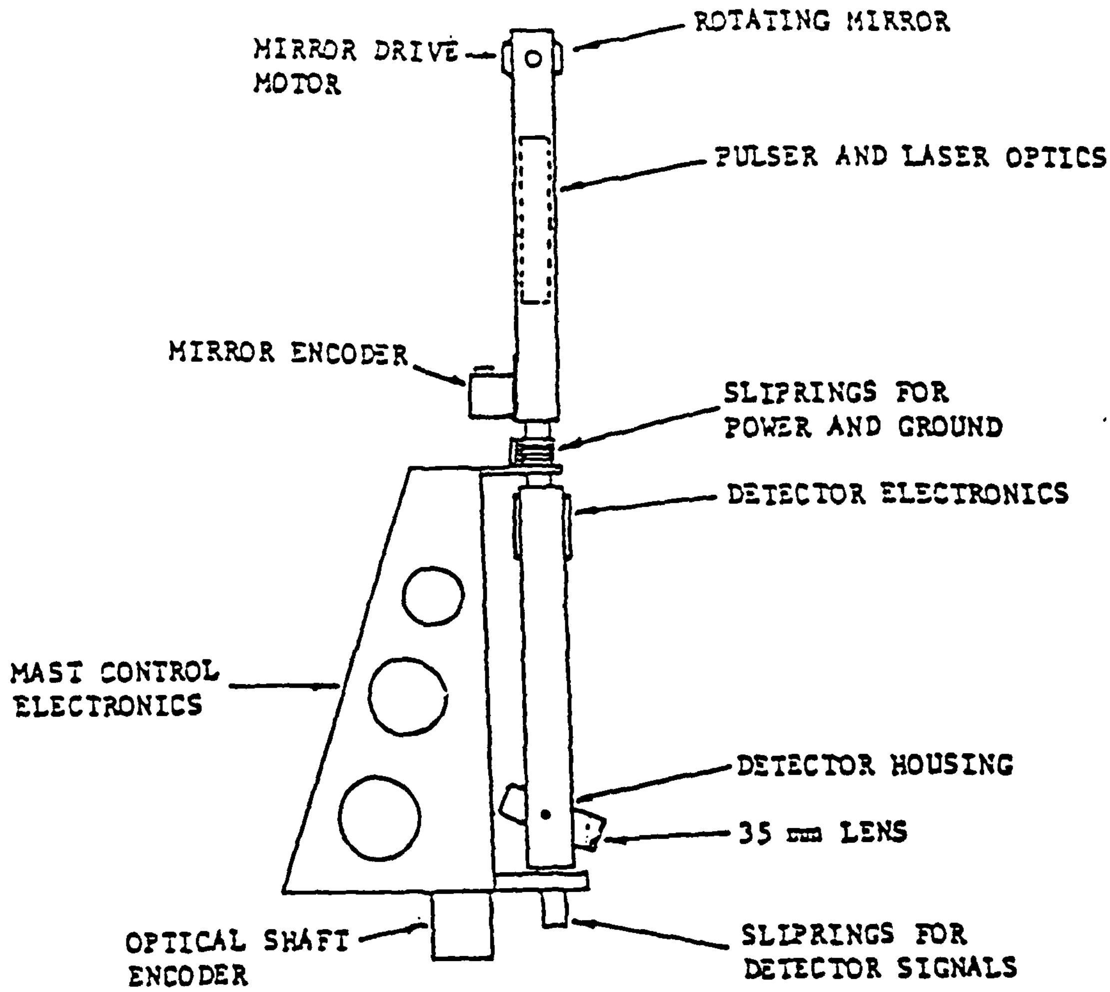


Figure 9. Components on the ML/MD mast

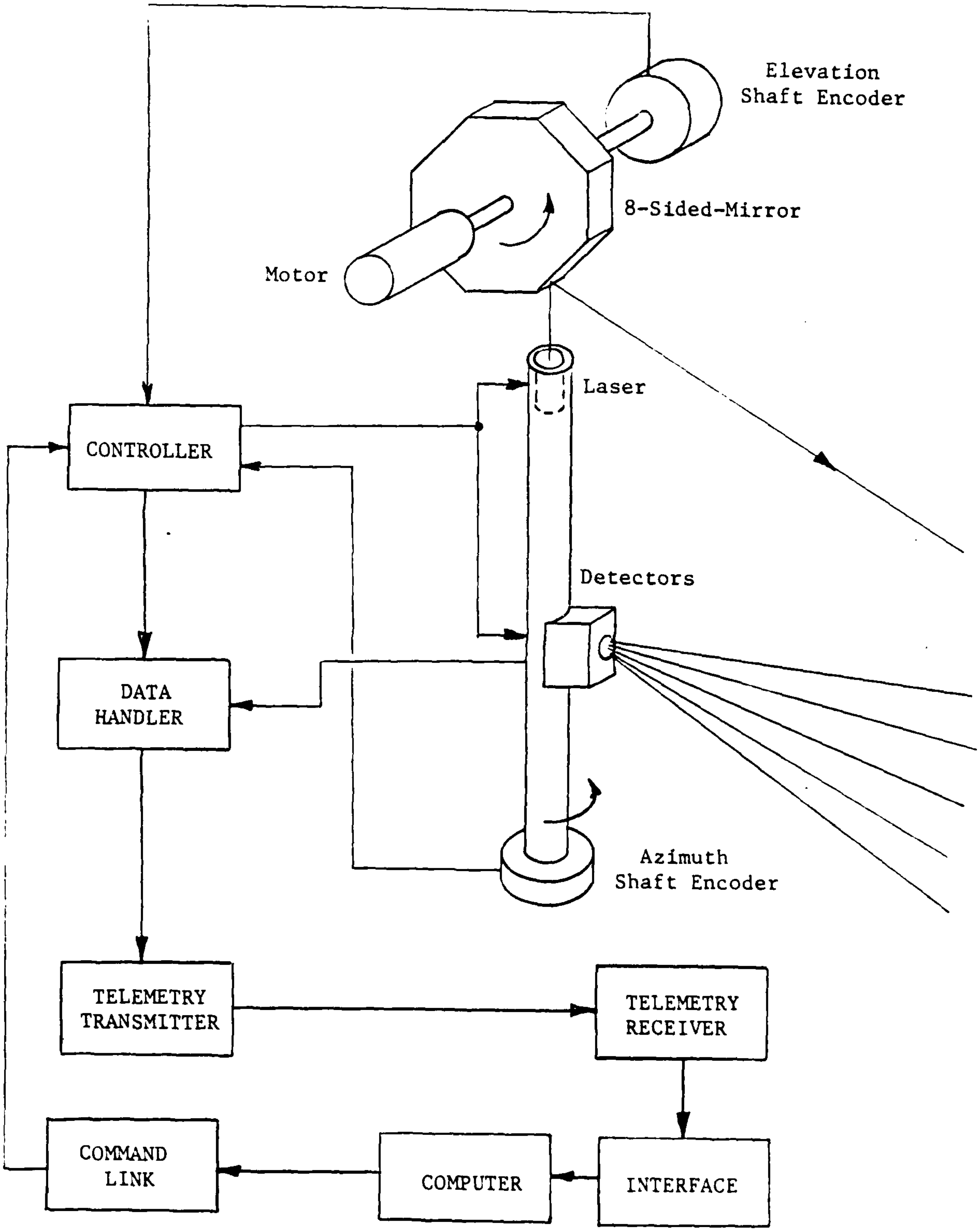


Figure 10. System elements and signal flow for ML/MD system

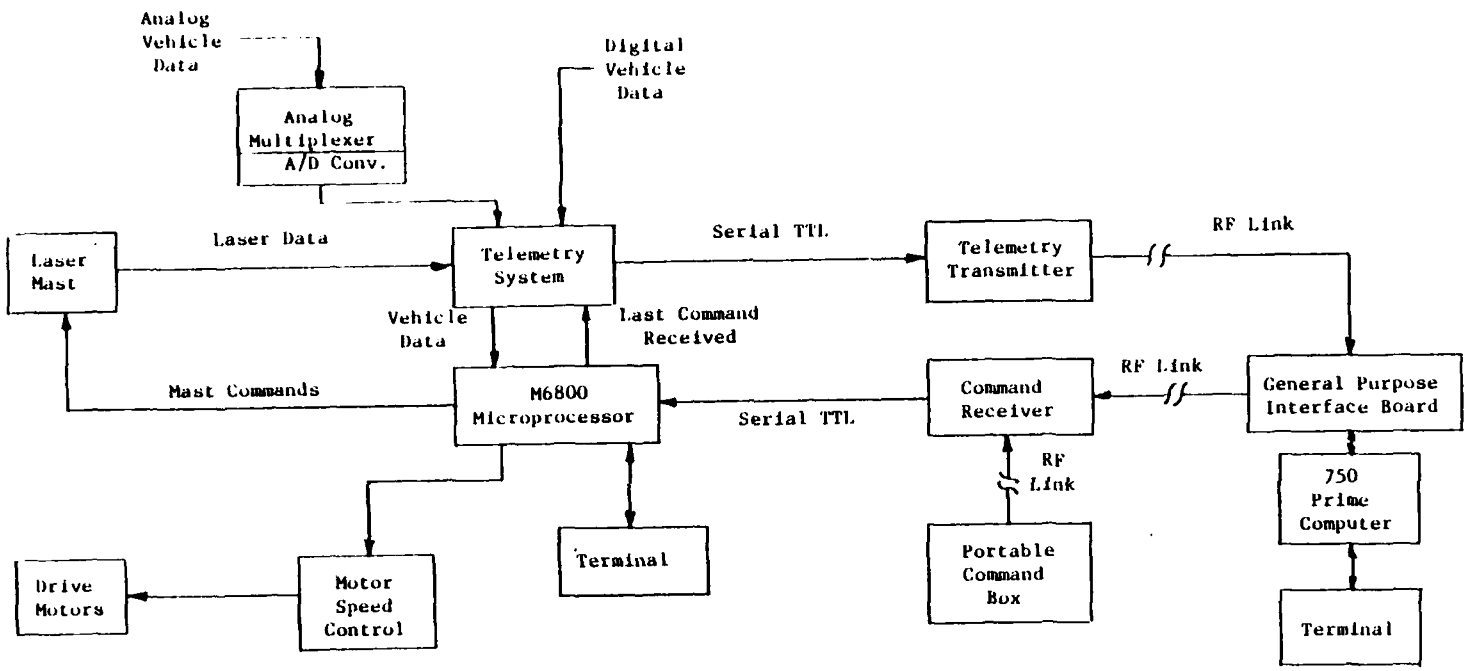


Fig. 11: Electronic System of vehicle and external equipment

in the vehicle's path. It supports optics and electronics that allow the laser to fire a matrix of laser shots on the terrain in front of the vehicle. The electronics controlling the mast are documented in Reports MP-59 [8] and MP-73 [10]. The laser is a pulsed type and the high current pulses can generate noise spikes in the other electronic systems. Because of this modifications were made to the original design to suppress that noise.

When the laser fires, the laser shot will generally be reflected back from the terrain. A detector is mounted on the mast which will receive reflections which are within its field of view. The detector consists of a 20-element photodiode array mounted behind a 35-mm camera lens and its total field of view is 30°. The outputs of the diode array are monitored by detector electonics described in Report MP-74 [11]. The electronics generate the identification numbers of those diodes that receive returns and these identification numbers are the data that are sent to the Prime computer.

The telemetry system transmits both vehicle and laser data to the computer so that programs running on that machine can determine what course of action to take, e.g., stopping the vehicle if it encounters a hazardous terrain feature. The telemetry system gathers analog vehicle data such as gyro angles through an analog multiplexer and analog-to-digital (A/D) converter. Digital vehicle data such as steering angle is sampled directly. The actual electronics are discussed in Report MP-72 [12].

In addition to sending data to the computer, the telemetry system also supplies certain vehicle data such as wheel speeds and gyro angles to the on-board microprocessor. The microprocessor, on the other hand, will echo the last command received so that the telemetry can send it to the Prime computer. This enables the computer to check that the microprocessor is receiving commands correctly. These data transfers between telemetry and the microprocessor occur

via a Random Access Memory (RAM) shared by both of them.

The microprocessor interprets commands from the computer or the portable command box, maintains proper wheel speeds to result in a given vehicle speed and steering angle, displays vehicle data on a terminal attached to one of its serial ports, formats telemetry data for its own use, and interprets information concerning the torque on each wheel (see Reports MP-77 [13], MP-70 [14], MP-76 [15], and MP-79 [16] for details).

Commands that the microprocessor receives may be for the laser mast or they may be specific vehicle commands. Laser commands could be used to change the dynamic performance of the mast as warranted by conditions during a run. Wheel speeds and steering angles are maintained by having the microprocessor generating the appropriate control signals after evaluating the vehicle data from the telemetry system. Torque information about each wheel enables the microprocessor to determine if that wheel is dragging (or spinning) and to increase (or decrease) the drive torque on that wheel appropriately.

The command link is the means by which programs running on the computer that are analyzing data from the laser mast and the vehicle can direct the vehicle's actions so that it can travel toward its target while avoiding obstacles in its path. Commands are sent from the computer to a radio transmitter in the rover lab. A radio receiver on the vehicle receives the transmission and passes the data to the microprocessor for command decoding.

The computer executes the high-level Fortran programs that control the vehicle during an autonomous run. The General Purpose Interface Board (GPIB) is the link between the telemetry system and the Prime computer (see Report MP-68 [17]). Its function is to provide a high-speed data path into the Prime via Direct Memory Access (DMA), enabling the implementation of control algorithms. By using a terminal attached to the Prime, any pertinent information can be displayed

while a run is in progress. Having given this overview of the electronic components of the rover and its supporting equipment we shall consider the individual components briefly in the following chapter. The reader will be referred to the appropriate technical reports for further details.

IV. THE MULTI-LASER/MULTI-DETECTOR SUBSYSTEMS

In this chapter we will describe the various subsystems comprising the multi-laser/multi-detector (ML/MD) obstacle detection and avoidance system that has been under development during the past several years. Because most of this work is documented in a series of reports, our discussion will be limited to the highlights, supported by the appropriate references.

We start with the laser and detector, followed by the mast controller, the data handler, and the steering and propulsion system. Then the telemetry data link, the computer interface, the real-time computer software, and the terrain modeler and path-selection algorithm follow. We conclude with a description of the dynamic test platform.

A. Laser and Detector

An opto-electronic receiver employing a 20-element linear photodiode array has been built and has been found to achieve a resolution of 1.5° over a 30° field of view and a 5-meter range.

Figure 12 shows an exploded view of the receiver's components, namely, the lens and its rotatable mounting, and the detector/preamp, comparator, and digital circuits boards. The functional block diagram in Figure 13 illustrates the signal processing performed by the receiver in transforming the reflected laser ray into a digital output suitable for telemetry to the modeler/path selection computer. Ideally, the lens, which is a 35 mm f/2.0 Pentax, focuses parallel rays into a single point in its focal plane. By vertically aligning photodiodes in the len's focal plane the elevation angle of the laser return can be determined by noting which diode responds.

The 20-element array consists of 20 photodiodes, each 0.9 mm x 4 mm,

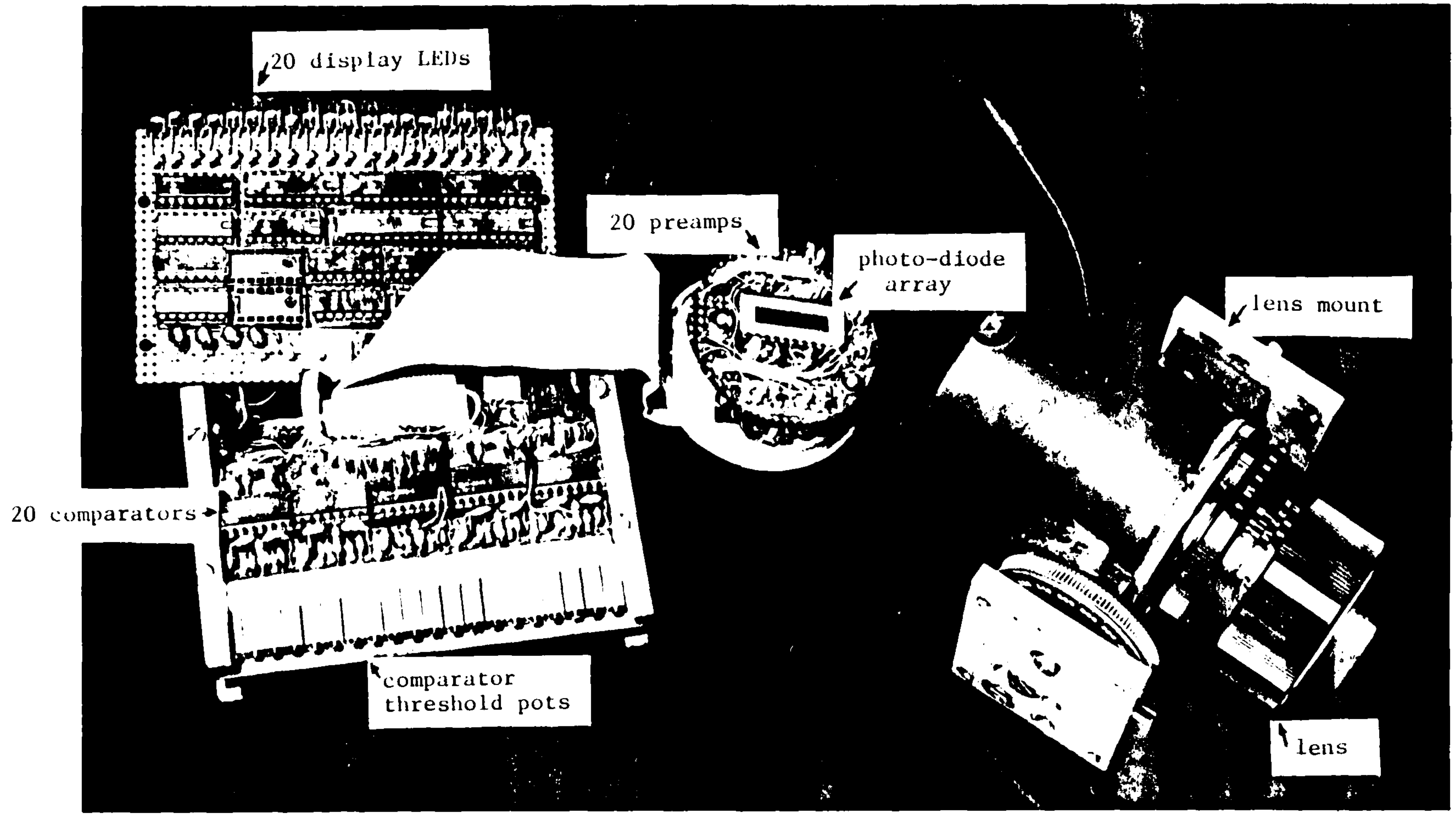


Figure 12: Components of the return signal detection system.

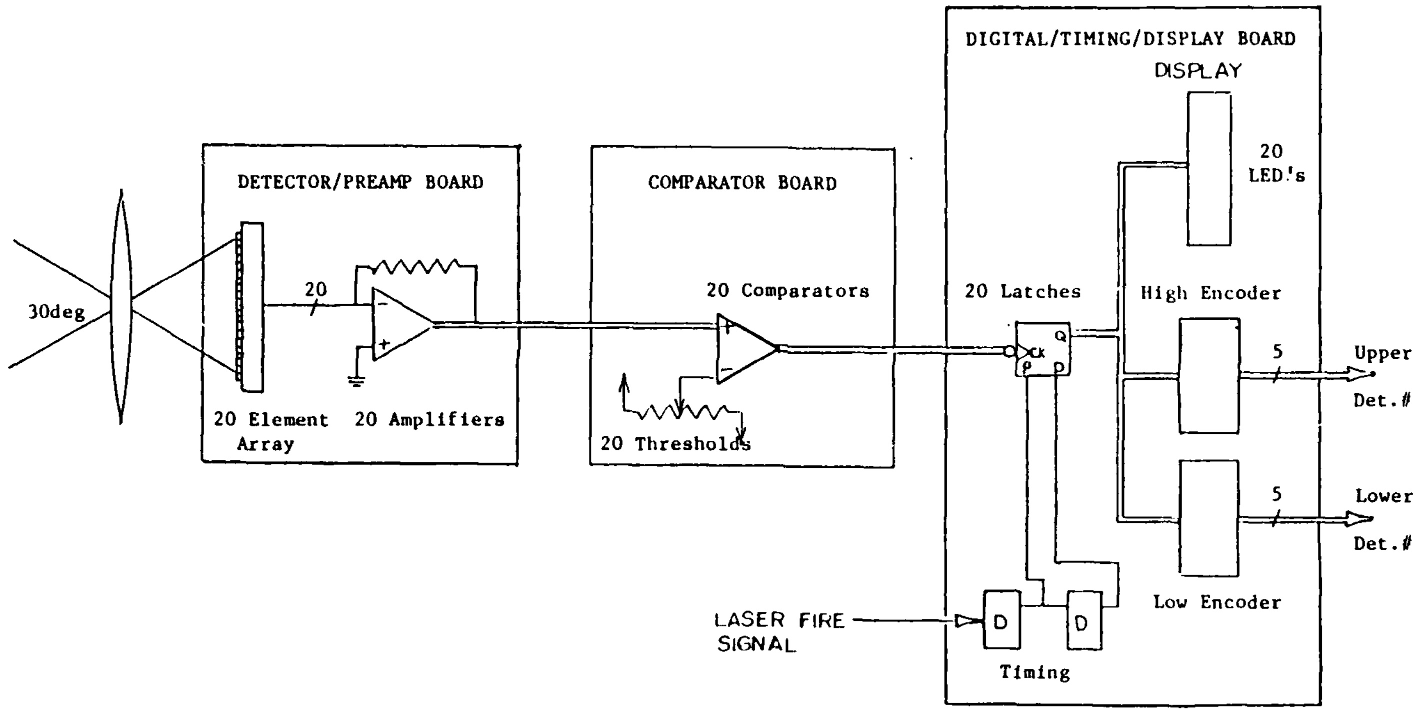


FIGURE 13. PHOTODIODE DETECTOR BLOCK DIAGRAM

mounted on 1 mm centers in a single 22-pin dual-in-line package. Located in the center of the preamplifier board on the optical axis of the receiving lens and reverse biased to 24 V DC, the photodiodes convert incident laser light into current at the 20 individual diode outputs.

The current pulses from the photodiodes are transformed into negative-going voltage waveforms by the 20 operational amplifiers configured as inverting current-to-voltage converters. Measured returns from poor reflectors at a 3-meter range exceeded 50 mv with an acceptable level of oscillation at the preamp output.

The amplified photodiode pulses are fed into the positive inputs of the 20 comparators and cause a low-going TTL level at comparator outputs whose pulse amplitudes go below the thresholds set on their negative inputs. The thresholds are adjusted by the voltage-dividing action of the 20 threshold potentiometers. The reason 20 individual thresholds are necessary is in part so that d.c. offsets can be nulled out. Also the individual adjustments allow for a correction of the lens roll-off, or vignetting, whereby the images received on the edges of the field of view are less intense than those closer to the optical axis. By lowering the thresholds of the channels associated with the off-axis elements they can be made more sensitive than the center photoreceptors, thereby widening the lens' rolloff characteristic. Furthermore, the separate thresholds allow the lower detectors, which normally operate at farther ranges, to be made more sensitive than the higher detectors. Thus each channel can be tuned to the expected signal level providing a large dynamic range over the array while minimizing the possibility of false returns.

The digital board accepts the 20 digitized channels from the comparator card and encodes the data to conform with the telemetry constraints. Five bits are generated to denote the highest diode excited and another five bits denote the lowest illuminated element. These two five-bit words are then concatenated into a

single ten-bit word that is sent to the mast controller.

Figure 14 is a plot of the amplifier outputs for all 20 channels as the receiver was rotated about a horizontal axis. These measurements were taken with a good reflector, the aperture wide open, and at a range of three meters. The variation in peak height from channel to channel is a result of device non-uniformity. The rounding of the individual peaks is indicative of both receiver defocus and relatively large laser spot on the reflector. There is considerable overlap between adjacent diode response curves and the thresholds must be set carefully if only a single return is desired. The problem is greatly complicated when a multiplicity of ranges and reflectivities are considered. Yet with proper adjustment of the lens aperture and the 20 thresholds, returns can be restricted to single returns and double returns from adjacent elements. It should be noted that the overlap increases the effective resolution of the detector since the number of possible returns has been increased to 39 (20 single returns plus 19 double returns). The double returns, provided for in the detector's encoders, can be exploited by the obstacle detection computer to effectively double the receiver's resolution.

B. Mast Controller

The multi-laser/multi-detector (ML/MD) scanning system can sample up to 1024 terrain points and thus provides a thousandfold increase in data gathering power over the previous SL/SD version. For each terrain point the detector returns a code representing that point's elevation. A key element in the ML/MD scanning system is the electronic controller that monitors the mast and mirror positions, fires the laser at the desired angles, and formats the telemetry data word for transmission to the Prime computer.

In August 1980 the ML/MD scanning system was installed on the dynamic test platform and interfaced to the Prime computer. The ML/MD controller scan

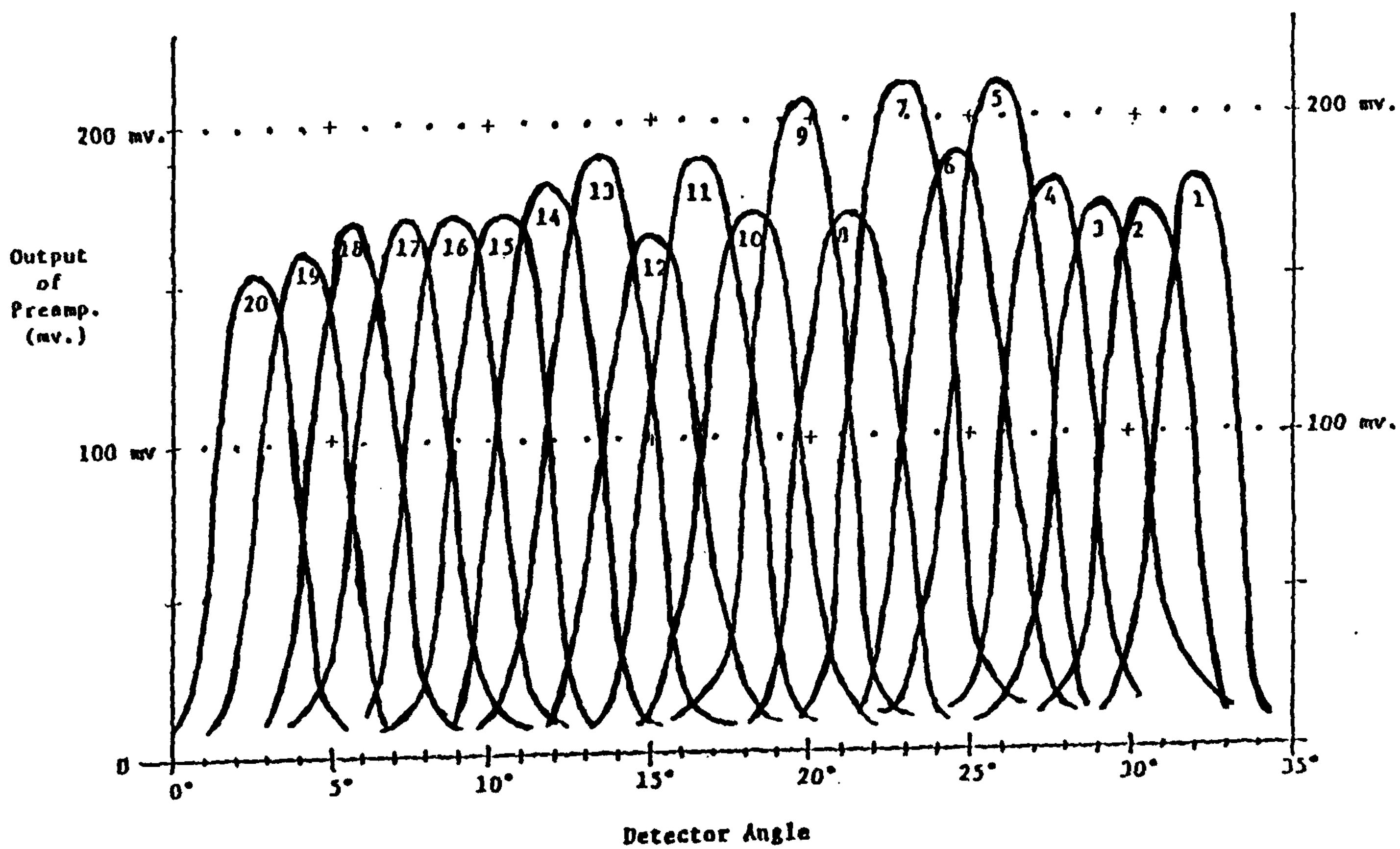


Figure 14. Signal Return vs. Elevation Angle of Source at a range of 3 meters

patterns may contain up to 32 azimuths with up to 32 elevation shots per azimuth. Laser pointing accuracy is 0.35 degrees in elevation and 1.40 degrees in azimuth. During the debugging process several enhancements were added to the controller. These include selectable scan patterns (4 each for elevation and azimuth) and scanning speeds (1, 2, or 4 seconds per scan or stopped). The laser can also be enabled or disabled.

Allowable scan patterns are limited by the laser firing rate and the ratio of mast and mirror speeds. In the current system the laser is limited to a 10 Khz firing rate and the mast-to-mirror speed ratio is 1:24. As a consequence, adjacent elevation firing angles must be at least 1.05 degrees apart. The minimum spearation between adjacent azimuth firing angles is 2.80 degrees.

The details of the mast controller and a description of the changes required in order to interface it with a proposed new telemetry and command-link systems are given in Reports MP-59 [8] and MP-73 [10].

C. Steering and Propulsion System

The steering and propulsion system of the rover has been completely redesigned in an effort to expand the vehicle control capabilities while at the same time adding flexibility. With this in mind, the system was based on a Motorola 6800 custom-designed system rather than a totally hardwired controller as was previously used. This microprocessor-based system performs three main tasks. First, it controls the vehicle, with its primary task being wheel speed control and steering angle. Second, it receives and decodes commands from the Prime computer. Finally, as a necessary elem... :f the control loop, the system collects vehicle data.

The specific vehicle functions under control of the steering and propulsion system include the individual wheel speeds (and thus the steering angle), and the

stepping gyroscope. The stepping gyro is controlled by the steering and propulsion system and has a potentiometer output that is linear over a 180° range. In addition, the gyro can be stepped around in two-degree increments providing a full 360 degree range. The system keeps track of where the gyro is, steps the gyro when necessary, and provides gyroscope information to the Prime computer.

The main function of the steering and propulsion system is to control the vehicle's wheel speeds and steering angle. Steering is accomplished by varying the speeds of the individual front wheels. The algorithm for computing these wheel speeds is implemented in the microprocessor software along with a proportional controller and discrete-time low-pass filter. Each wheel is driven by a 24-volt DC motor and the power delivered to each wheel is varied by using a variable duty-cycle pulsed voltage. The duty cycle can be varied from zero to 100 percent in 128 discrete steps. This yields much higher wheel speed and steering-angle resolution than the previous system that had only 16 discrete duty cycles.

The data needed for control purposes, which includes wheel speeds, steering angle, and gyro angle, are collected by the telemetry system for transmission to the Prime computer. The steering and propulsion system has control of a shared random-access memory (RAM) which is on the data bus of the telemetry system. The microprocessor enables the RAM to the telemetry which writes the required data and then regains control and reads the data. Hence the communication path is bidirectional. Currently, only commands from the Prime computer are echoed back through the shared RAM.

The command link from the Prime is based on a frequency-shift keyed (FSK) transmitter. The receiver on the rover converts the signal to a TTL-level serial stream for the steering and propulsion system's asynchronous communication interface adapter (ACIA). The command format has been expanded to eight bits from the old format of seven bits. Commands are software decoded, with

multiple-byte commands being supported. The command decoder was designed with the intent of making it easy to modify commands, add new commands, or rearrange the command format. With this ease of modification, plus the multiple-byte capability, the major constraints of the old hardwired decoder have been eliminated. One important outcome, was the definition of a new two-byte steering command, allowing the selection of steering angles in 1.40° increments as opposed to the 12.0° increments of the old system.

The major highlights of the new steering and propulsion system include a higher resolution of steering angle that allows the path- selection algorithm in the Prime computer greater leeway in determining a safe path, higher resolution in wheel speeds that is needed for obtaining the tighter steering increments, and finally, the flexibility obtained by having most functions performed in software rather than in hardware. The original design of this system and an analysis of the dynamic behavior of the velocity control system are in Report MP-77 [13]. More current descriptions of the hardware and software are given in Reports MP-70 [14], MP-76 [15], and MP-79 [16].

D. Telemetry Data Link

The telemetry data link and the general purpose interface board (GPIB) that resides in the Prime computer allow data that originates in the vehicle to be transferred at a high rate to the computer. The total system can be divided into two portions, namely, the transmitter and the receiver.

The transmitter is located on the rover and is an integral part of the vehicle's electronics package. It consists of two Motorola-compatible Exorcisor-type circuit boards. One board is basically a data acquisition system with an analog multiplexer and A/D converter. This card sequentially selects the data source and puts this data into a rate-buffering first-in first-out memory (FIFO).

Information is stored in a 16-bit address and 16-bit parallel data format. The channel selection is determined by a programmable read-only memory (PROM), so the vehicle data can be sent in any order desired by the user.

The second transmitter board has the electronics that interface with the steering and propulsion microprocessor bus. Also this board contains the system clock, a priority circuit that selects the laser mast when it desires service, and assorted control logic, including bus drivers and multiplexers. An advanced data-link control chip is included that performs the functions of error coding and parallel-to-serial conversion.

The timing constraints for the system are largely set by the laser scanning mast that must be serviced periodically to empty its rate buffers. The data link has been successfully run at bit rates of 640 kilobits per second, or 10,000 words of data per second.

The serially encoded data can be sent to the decision-making computer via coaxial cable or through a biphase modulated radio transmitter. The receiver portion of the link is on the GPIB of the Prime computer. The heart of this network is another advanced data-link controller operating in the receive mode. The serial data is decoded and then fed to the interface circuitry where the information is written into the computer memory in the direct memory acccess (DMA) mode.

Throughout the design process flexibility for future expansion has been considered. Three-state buses were employed in case additional hardware is desired such as a dedicated microprocessor for communication functions. Sixteen-bit address and data words are used for a greater number of possible channels.

The telemetry system has been used in the lab on the scanning mast platform with data relayed from the Mars Rover Lab to the Prime computer via coaxial lines. This has provided a good test set-up as well as a means of evaluating

systems on the test platform. It was here that actual performance measurements were made.

Integration of the system onto the roving vehicle has been eased through the use of an interconnecting box. All input/output lines are available at this box for diagnostic and modification purposes. Work is being done to further reduce the size of the data acquisition system by taking advantage of newer technologies. Also greater versatility and compatibility is being investigated through the use of a dedicated microprocessor data link controller. The reader should consult Report MP-72 [12] for the details of the telemetry data link.

E. Interface with the Prime Computer

To communicate with the rover it became necessary to build a new computer interface [17]. For the hardware part of the interface, a general purpose interface board (GPIB) was purchased from Prime and mounted in the computer frame. The GPIB enables the use of programmed input-output (PIO), standard and vectored interrupts, and a set of direct memory functions (DMX, DMA, DMC, and DMT).

DMA denotes direct memory access, where the starting address and word count are kept in the register set. Up to eight DMA channels (total) can be supported. DMC is very similar to DMA, and stands for direct memory channel. In this case the starting and ending addresses are stored in high speed memory, providing up to 2000 DMC channels. DMT is direct memory transfer, where the data address and word count are maintained external to the computer. The address must be applied to the bus with the data when requesting a DMT. This allows a random accessing of memory. In our case, DMT is preferred because the laser data returns will not be in any particular order. This is because the mast controller fires the laser as soon as the angular position of the mirror corresponds to one of

the desired elevation angles.

A block diagram of the interface is shown in Figure 15. Each telemetry data word received by the interface is composed of 16 bits of information and 16 bits of address or identifier. The address also contains any mast interrupts such as end of scan or end of azimuth. This 32-bit word is received in serial and converted to parallel. In the upper level interface, a portion of the address will be concatenated with a register containing an offset address into real memory. DMT will be used to put the data into memory. Finally there will be one vectored interrupt which uses a status register to identify various conditions such as mast interrupts, data overruns, or timeouts.

F. Real-Time Software

The new real-time software has been written on the Prime computer and is intended for the higher level interface (see Report MP-65 [18]). The objective of this real-time software is to implement control of the ML/MD rover and to record the raw data from the rover. Figure 16 shows the flow of information to and from the rover. Most of the software is written in FORTRAN, although routines were written in assembler language.

The important features of typical complete revolution of the mast are shown in Figure 17. The basic data consists of an interrupt status flag, laser data, and vehicle. The possible interrupt status flags, their meanings, and appropriate actions are:

EOA: End of azimuth; the data consists of laser returns and vehicle state information for a particular azimuth, i.e., for one set of elevation angles.

EOS: End of scan; same data as EOA, but also signals that a full scan has been completed.

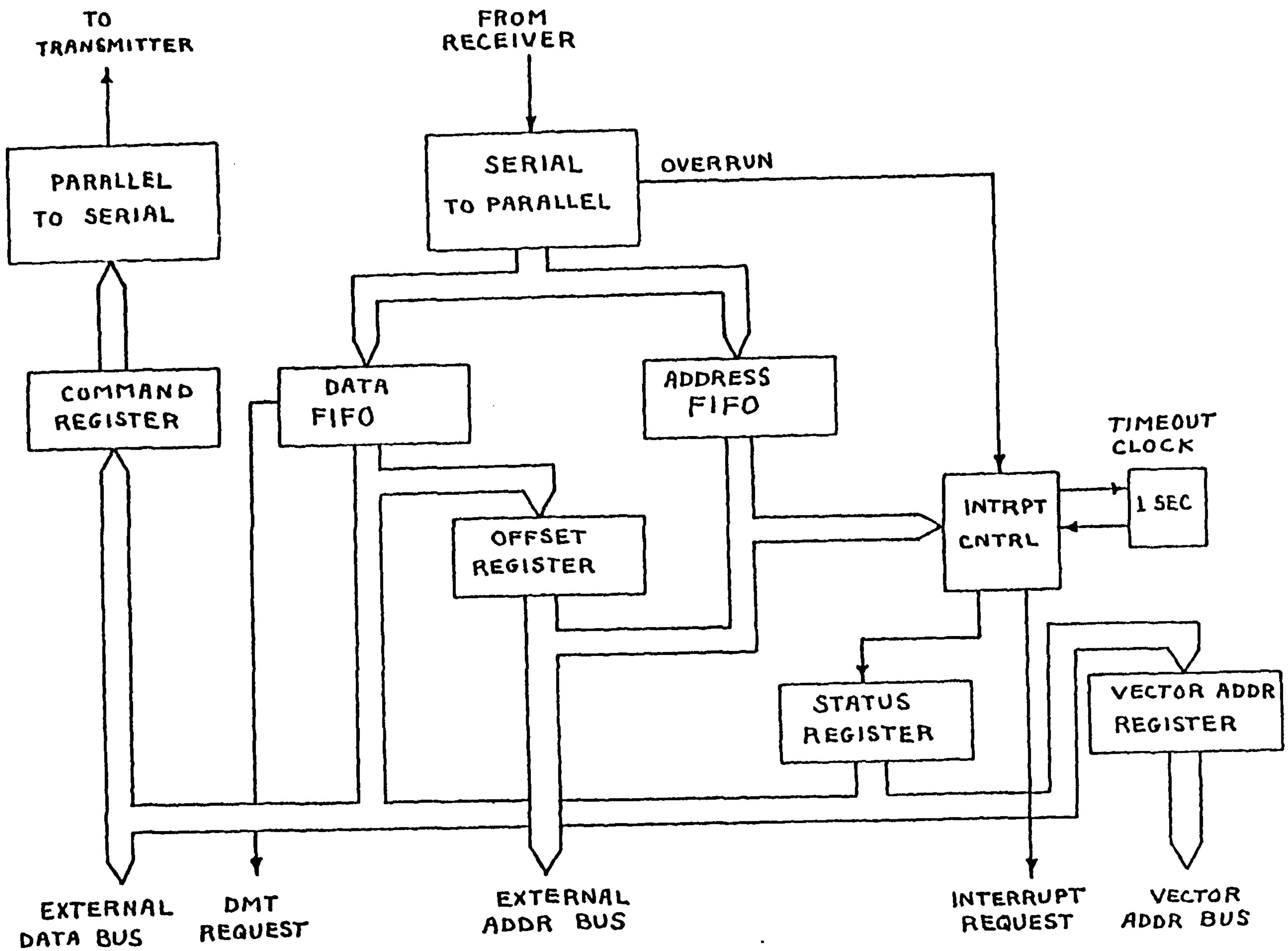


Figure 15. Telemetry Interface with the Prime Computer

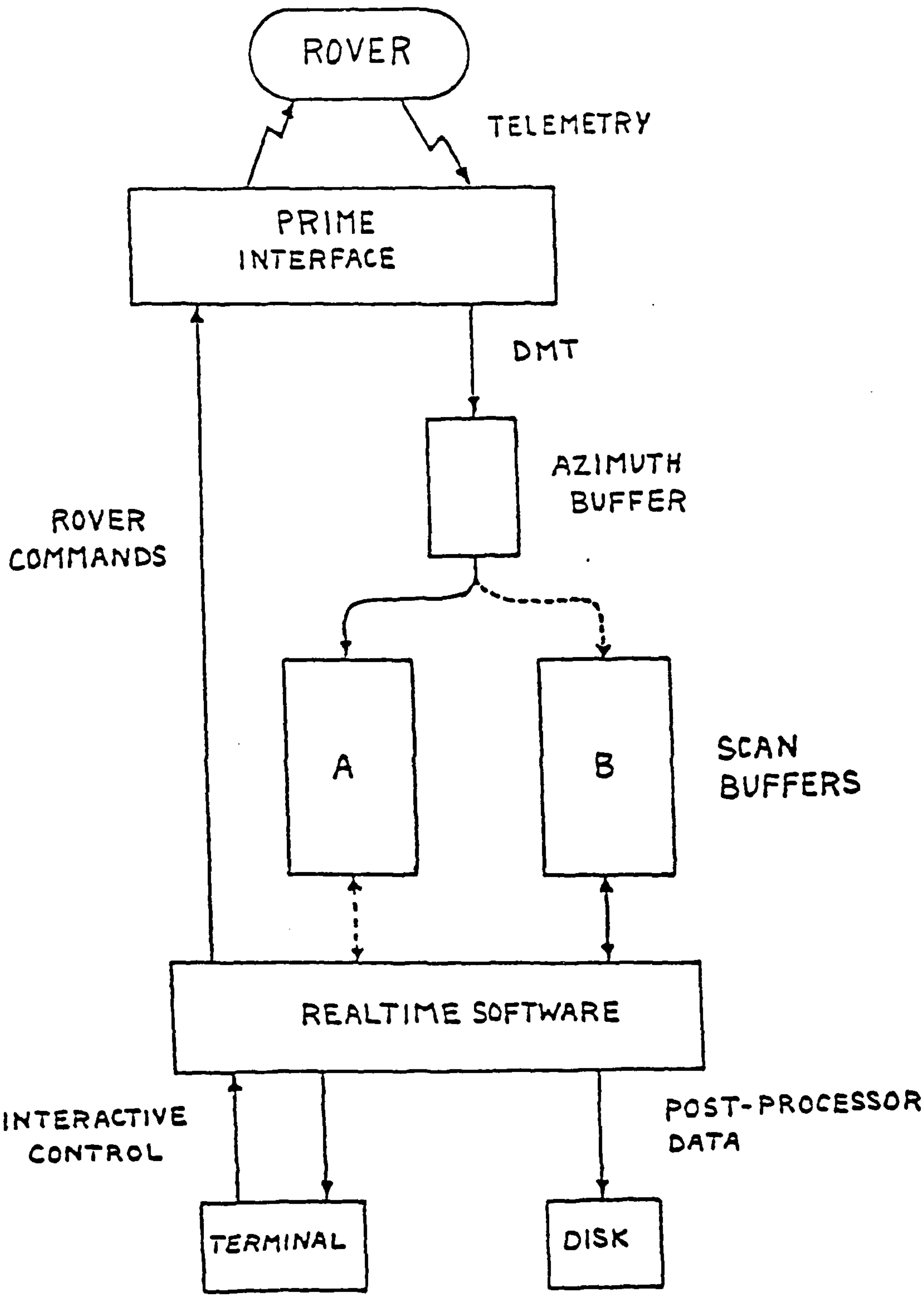


Figure 16. Information Flow in the Hardware - Software Interface

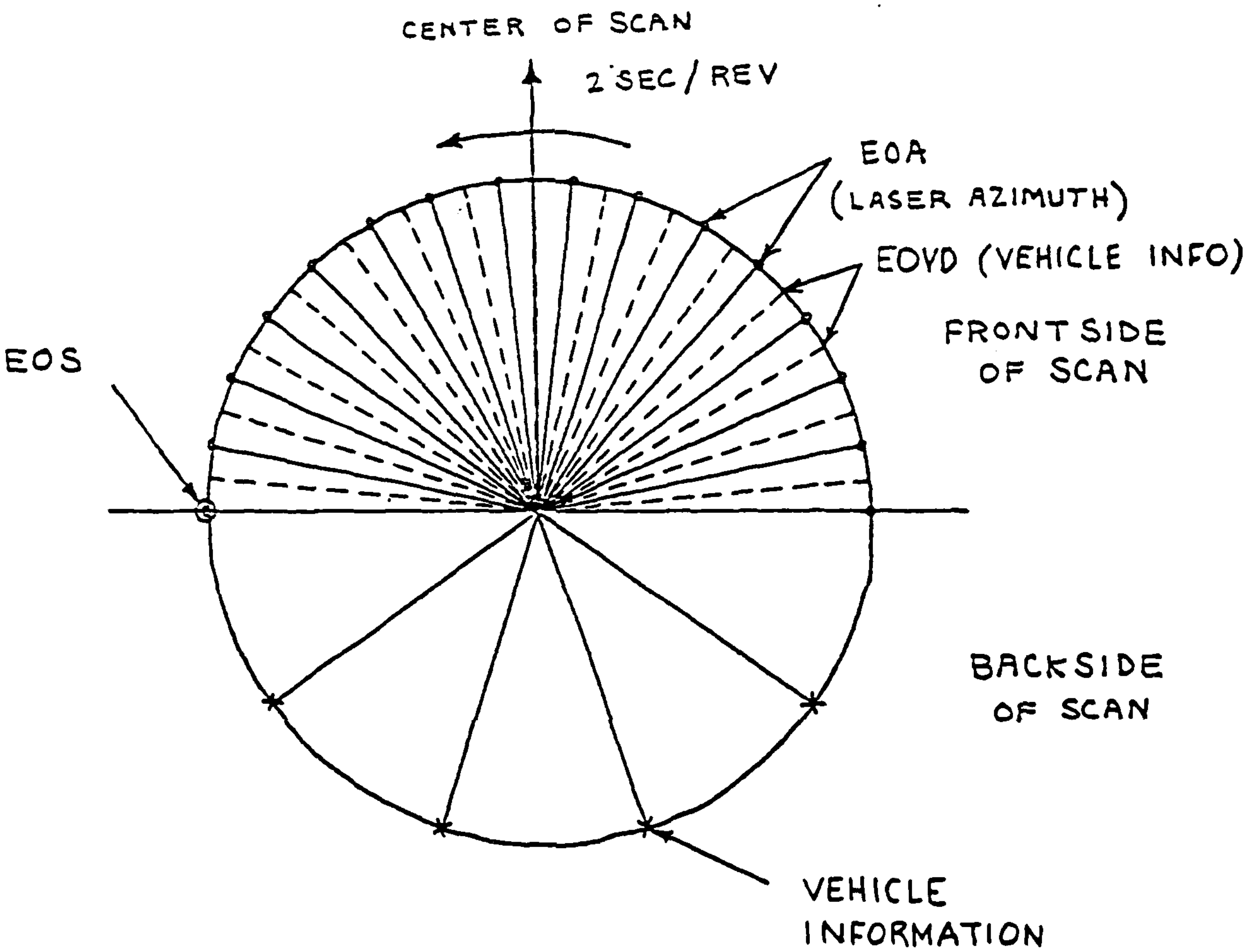


Figure 17. Scan Timing as a function of mast rotation

EOVD:	End of Vehicle Data; the data consists of vehicle state information only; no laser data is present.
Timeout:	No interrupts have been received for at least one second; it signals a possible hardware problem so the vehicle should stop.
FIFO Overflow:	New data has written over old data before the old data was read; the vehicle should stop and wait for the next EOS before accepting new data.

Telemetry data entering the GPIB is first stored in a FIFO (First-In First-Out) buffer, one block of data at a time. Each block consists of one laser azimuth or one set of vehicle data. When laser data is available from the mast, the telemetry transmitter on the vehicle will transmit one complete laser azimuth, followed by an EOA interrupt. When laser data is not available, such as in between azimuths or during the back of scan period, the telemetry will transmit blocks of vehicle data, each block terminated with an EOVD interrupt.

Upon receipt of an interrupt by the telemetry receiver on the GPIB, the block of data received will be transferred into the Prime's memory via a DMT operation into one of two scan buffers. This provides a double-buffering scheme such that the software can be processing data from one scan while the data from the next is being received and stored in the other buffer.

Figure 18 gives a flow chart of the real-time system. The main routine, called EXEC, is in charge of the entire system flow. After the user gives the RUN command, the system is initialized. The system then waits for an interrupt to signal that some data is available. After an interrupt, NAVIG is called to convert the data to a usable format and to perform navigation. If an EOA interrupt occurs,

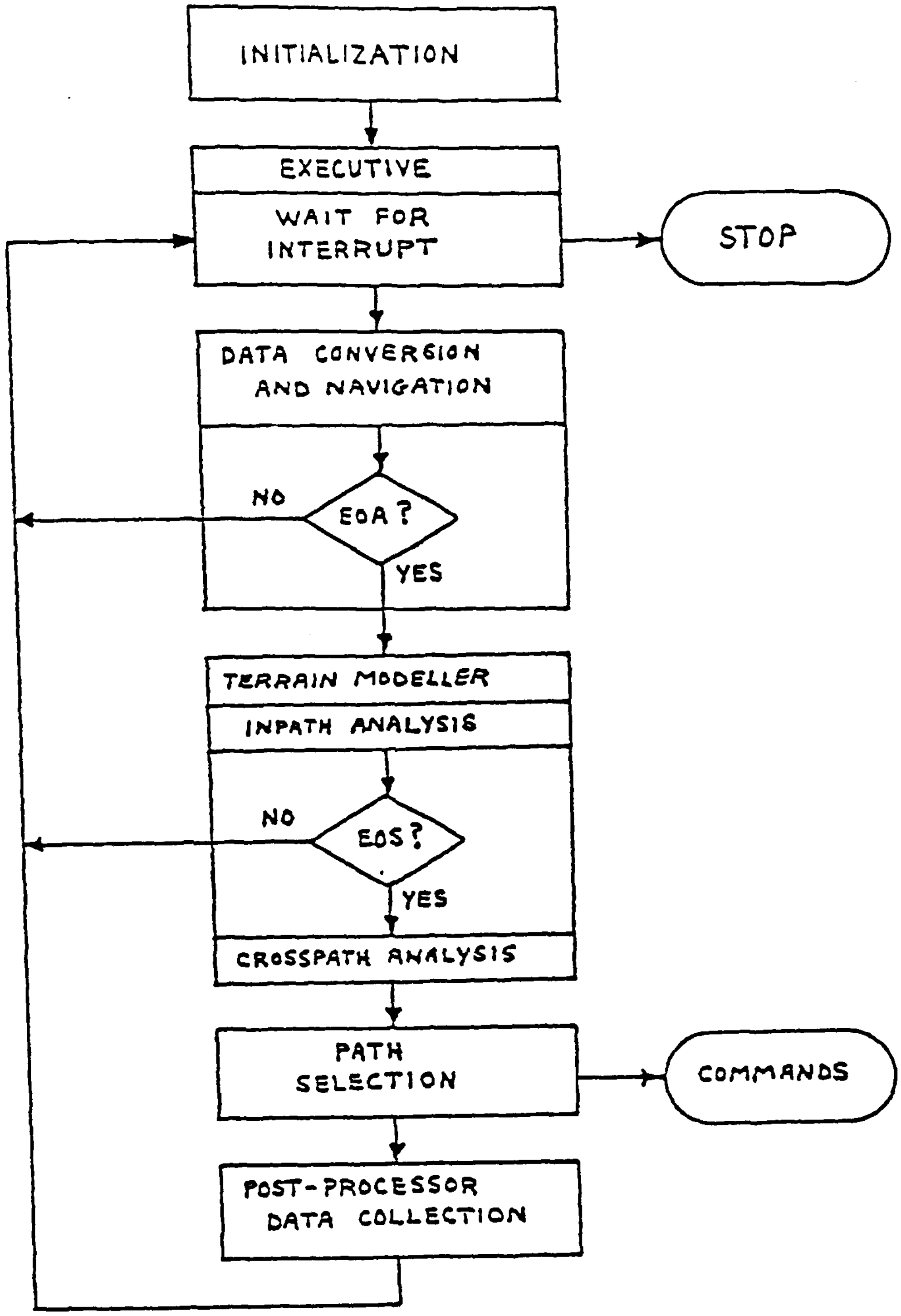


Figure 18. Flow chart of real-time software

then the data includes laser returns and the MODEL routine is called to analyze these returns.

The terrain modeller analysis can be further broken down into inpath and crosspath components. The inpath component is along a single azimuth and can be done for that azimuth as soon as the data has arrived. Because the crosspath component involves more than one azimuth it is done only after the EOS interrupt occurs. If an EOS occurs, then after performing a crosspath analysis the modeller will pass its results to the path selection routine (PSA). Using both current and past information, the PSA will select an appropriate path and send the corresponding steering command to the rover. Finally the data will be saved for the post-run analysis and the process repeated.

A Primos system subroutine, T$ROVR, was written as an I/O driver for the Rover GPIB. This subroutine enables realtime software routines running on the Prime to communicate with the Rover vehicle via the GPIB interface.

T$ROVR operates in a completely transparent manner to the real-time software. In this way, the only actions that need be taken by software are calls to T$ROVR to initialize it, and to signal when all the data in a scan buffer has been processed. T$ROVR will not overwrite any data in a buffer until it has been released by the software routines. If both buffers become full, T$ROVR automatically sends a "STOP" command to the vehicle. As soon as the next buffer becomes available, T$ROVR sends a "START" command to the vehicle and resumes the collection and storage of data.

T$ROVR makes GPIB status information available to the software on a real-time basis. It also stores this status in special buffer sections along with each stored section of laser and vehicle data, reflecting GPIB status at the time that data was received.

Another important function of the GPIB made available through T$ROVR is the transmission of commands from the real-time software to the vehicle. All communications between the vehicle and the real-time software are handled through these devices. For more information on T$ROVR, see Potmesil [19].

G. Terrain Modeler

Looking ahead to the need for a more sophisticated terrain modeler for use with the ML/MD system, studies were begun in 1976 by Krajewski [20] and continued by Maroon [21], Troiani [9] and Hunter [22]. Hunter refined Troiani's modeler and implemented a crosspath analysis to detect very large obstacles that would affect the roll of the vehicle. Negative hazards were still not readily detected, slope estimates were good to within ten degrees, and slopes with obstacles continued to create problems for the area-slope manipulations. Although in the very near field (less than one meter) objects were easily identified, this did not leave the vehicle enough time to avoid small obstables. Furthermore, each of these modeling attempts encountered problems with its slope estimations when terrain steps were present. This was due to the quantization errors that are inherent with a laser/sensor data collection system of the type used on the Mars Rover. Messing [23] found that these errors could be greatly reduced and almost eliminated by using a thinning algorithm to remove data points that are too closely spaced (in range) before any further processing was performed.

The heart of the current modeler is a dual filtering scheme that essentially separates the problems of identifying step and slope hazards. The returns from the scanning elevation mast are known height and range points and this raw data is lightly filtered for the terrain height estimates. These data are examined for sudden steps that the rover might not be able to climb. Some raw data is more heavily filtered, thereby forming a series of more slowly varying points that are

used for the slope estimates. Figure 19 depicts the logical flow of the modeler and the principal steps involved.

The results of initial computer simulations indicated excellent predictions by the modeler of the actual terrain. Boulders and craters were distinguishable to within a few centimeters, and slopes (both up and downhill) were determined to within one or two degrees. The fact that negative obstacles were more readily apparent is significant in itself as several earlier modelers had problems detecting them. A crosspath obstacle detection algorithm that had been implemented also was found to work extremely well and crosspath hazards were easily avoided.

A second round of simulations involved moving the rover over a variety of surfaces consisting of: sinusoidal terrain with a period of several vehicle lengths, smooth terrain with boulder and crater obstacles, rubble strewn boulder-crater fields, and finally realistic Martian landscapes. The modeler performed well under all of these circumstances, flagging hazards to be avoided by the path selection algorithm.

Details of the modeling algorithm and the simulation results obtained are given in Report MP-75 [24].

H. Path-Selection Algorithm

The path selection algorithm for the ML/MD system is essentially the same as the one developed for the SL/SD system that was referred to in Sec. II B and is described in report MP-61 [3]. The flowchart of Fig. 20 shows the important steps in the algorithm.

Before any scans are made, an initialization call is used to set up the laser field of view and the increment between azimuths. The coordinates of the target point are given relative to the rover's initial position, which is taken as the origin

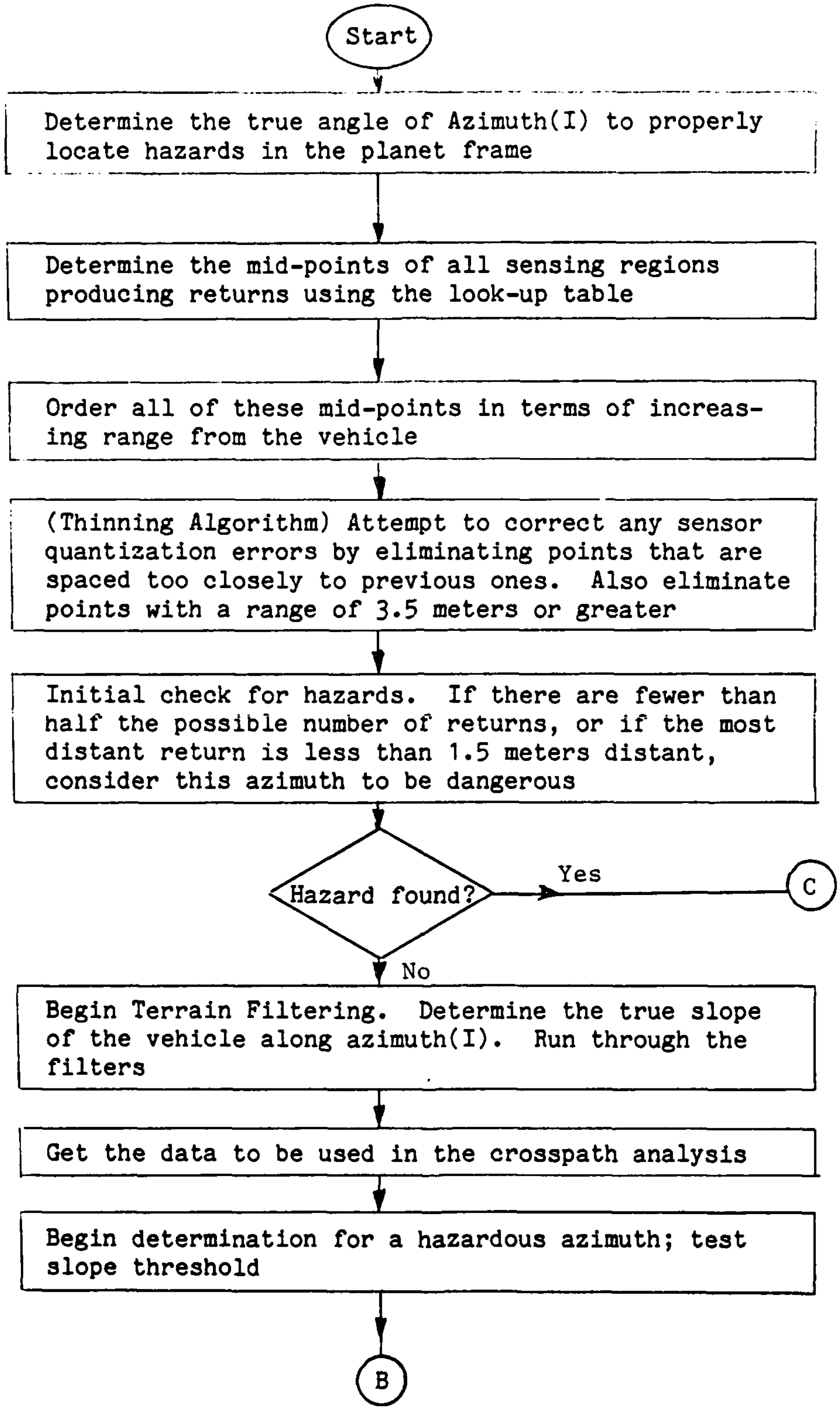


Figure 19a. Flowchart of terrain modeler

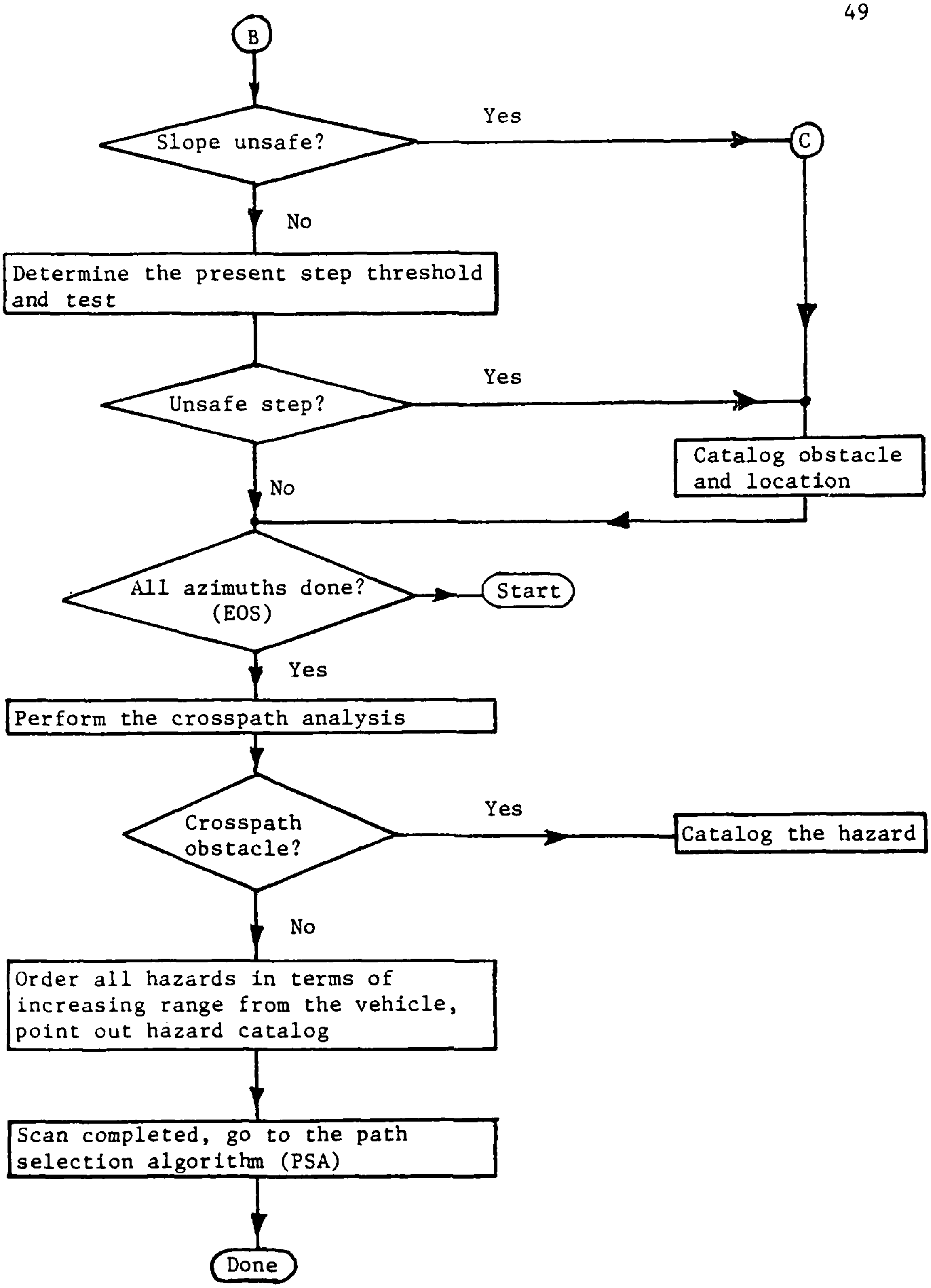


Figure 19b. Flow chart of terrain modeler

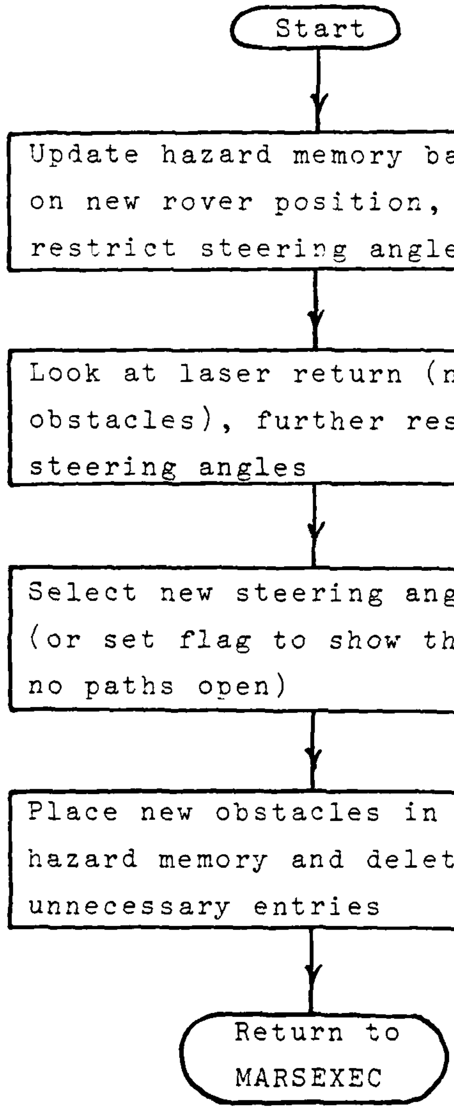


Figure 20. Flowchart of path-selection algorithm.

(the rover is initially pointed in the +Y direction). Control then returns to the real-time program EXEC.

Processing of a laser scan begins with an update of the hazard memory based on the new rover position. The hazard memory contains four pieces of information for each obstacle, namely: the X and Y coordinates of the obstacle (relative to the origin), the worst-case steering angle that would enable the rover to just miss the obstacle, and an obstacle status flag. The status flag indicates one of three possible conditions: no obstacle (this slot in hazard memory is open), an active obstacle (not behind the vehicle), or inactive obstacle (behind the vehicle). Since the worst-case steering angles and status flags depend on the current rover position and heading, they are recalculated every time the path selection routine is called.

After the hazard memory has been updated, the range of possible steering angles to be considered is restricted to be within the worst-case steering angles of the active obstacles. Therefore, the rover should successfully avoid obstacles that have been sighted previously.

The next step in the algorithm is to break up the new laser return into obstacles and to calculate the worst-case steering angles for these hazards in the same manner as was done for the hazards already in memory. The range of possible steering angles is then further restricted to be within the worst-case steering angles of these new obstacles. We are now in a position to select the new steering angle. Specifically the new steering angle is that which is closest to the target angle but still satisfies all of the constraints imposed by the old and new obstacles. However, if no angles can be found that satisfy all of the constraints, then all paths are blocked and no steering angle can be generated.

With the new steering angle selected, only clean-up chores remain. The new obstacles are stored in the hazard memory and those obstacles that have "covered" by new obstacles are removed in order to free space in the memory. If desired, the results of the scan are printed at the user's terminal. Finally, control returns to the EXEC operating system and the computer waits for a new set of data from the mast.

I. Dynamic Test Platform

In order to be able to fully test, study, and refine the advanced scanning system a dynamic test platform fixed in the laboratory was designed and built. This platform is intended to emulate the rover behavior on irregular terrain surfaces by subjecting the elevation scanner to a variety of time-varying attitudes and motions. These are similar to the perturbations it would experience if mounted on the rover as the latter negotiates irregular ground. The advantage is that the perturbations are predetermined, controllable, and repeatable. These features enable studying the ML/MD's performance characteristics without the randomness and ambiguity of the field test to cloud the study.

The platform, as shown in Figs. 21 and 22, provides a mounting surface for the ML/MD system that can oscillate simultaneously in roll and pitch with adjustable amplitudes and frequencies. Also, the position of the mounting surface can be adjusted both vertically and longitudinally with respect to the axes of rotation. To simulate the motion of the vehicle with respect to terrain, three-dimensional terrain models can be moved toward the platform at controlled velocities. The details of the platform's design and construction and a discussion of the manner in which its performance specifications were derived so as to simulate anticipated vehicle motions are described in Ref. 25.

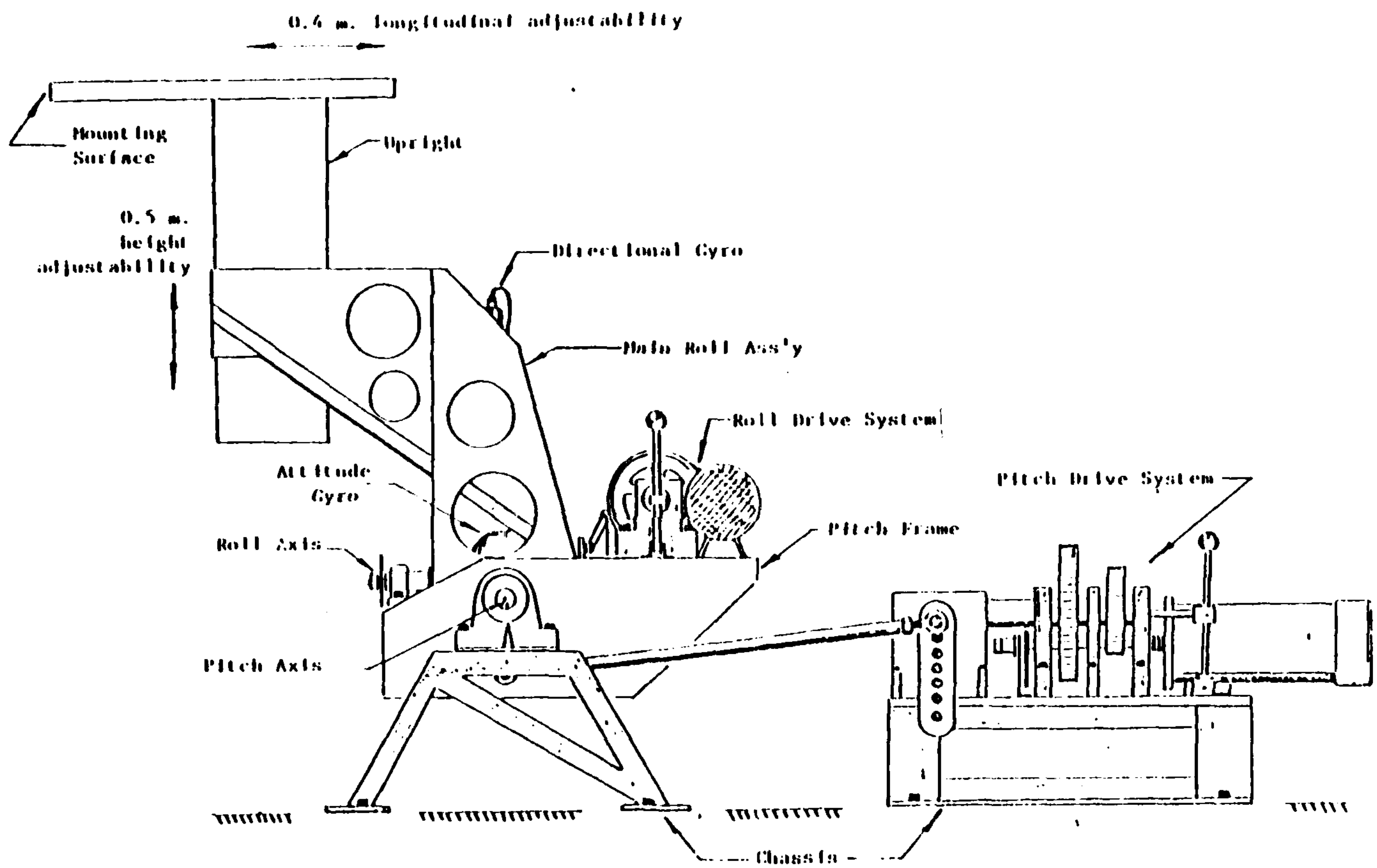


Figure 21. The Dynamic Test Platform

MAST MOUNTED ON THE DYNAMIC TEST PLATFORM

Figure 22

J. Evaluation Testing

A program for the evaluation of the capabilities, limitations, and resolution of the vision system began with a careful review of the performance of the subsystems involved. Repairs were made when required, and in some cases design deficiencies were uncovered and resolved by appropriate modifications. These efforts are discussed inn Report MP-80 [26]. This report also points out that although the elevation field of view of the current mast arrangement is 30°, that may not be wide enough. The maximum slope (assuming a sudden onset) observable by the detectors is now $\pm 17^{\circ}$, which is appreciably smaller than the suspension is capable of handling.

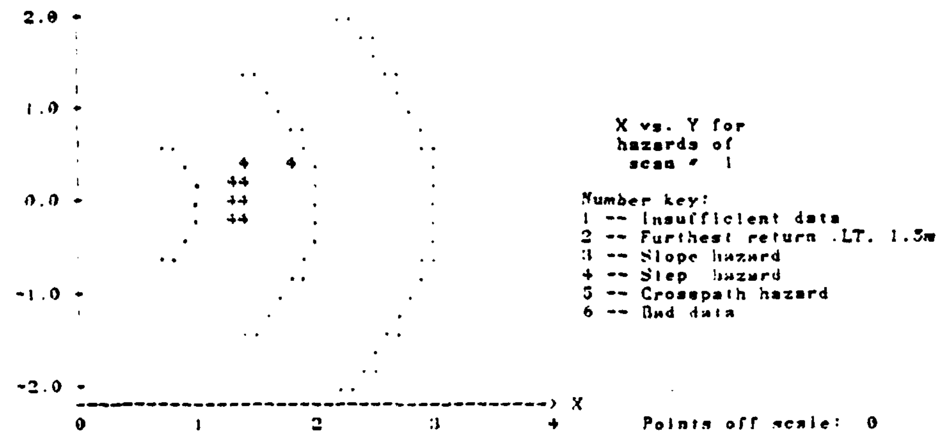
Vision system testing was performed indoors with the mast vertical and 36 cm higher than its nominal position on the vehicle. This was done in order to permit "holes" up to 36 cm deep to be produced easily. Artificial terrains were created using cardboard sheets and boxes with reflective properties simmilar to dry dirt. The floor was smooth concrete. The test terrains used and detailed parameter conditions are described in Report MP-82 [27]. A summary of the results follows.

With a single rectangular step hazard simulated by 66 cm x 61 cm boxes with heights from 5 to 45 cm placed 1 meter in front of the mast, heights of 20 cm and lower were not detected, but 25 cm and higher levels were all considered hazards by the modeler program. Figure 23 is an example of the form of the output data for the 25 cm height case.

Slope tests were performed using a 66 x 183 cm ramp starting 1 meter in front of the mast. The ramp slope was varied from 5° to 40°. The results show that between about 25° and 30° slope, the ramp begins to appear as a step hazard at about 1.5 meters, with a few crosspath hazard points appearing earlier.

```
Input file: MDL.STEP.12
File Creation Date : WED. JUL 27 1983      System time   14:05:35

          ** MODEL1 PARAMETERS **
   HEIGHT FILTER COEFFICIENT =          0.25
   SLOPE FILTER COEFFICIENT  =          0.90
   LEVEL GROUND STEP THRESHOLD =        0.25 METERS
   SLOPE THRESHOLD =                   30.00 DEGREES
```



AZIMUTH	(deg)	RANGE	X	Y	Z	HAZARD TYPE
1	-43.56	N O	H A Z A R D S		C A T A L O G E D	
2	-40.74	N O	H A Z A R D S		C A T A L O G E D	
3	-37.93	N O	H A Z A R D S		C A T A L O G E D	
4	-35.13	N O	H A Z A R D S		C A T A L O G E D	
5	-32.31	N O	H A Z A R D S		C A T A L O G E D	
6	-29.50	N O	H A Z A R D S		C A T A L O G E D	
7	-26.69	N O	H A Z A R D S		C A T A L O G E D	
8	-23.88	N O	H A Z A R D S		C A T A L O G E D	
9	-21.08	N O	H A Z A R D S		C A T A L O G E D	
10	-18.26	N O	H A Z A R D S		C A T A L O G E D	
11	-15.45	N O	H A Z A R D S		C A T A L O G E D	
12	-12.64	N O	H A Z A R D S		C A T A L O G E D	
13	-9.84	1.37	1.35	-0.23	-0.34	Step hazard
		1.45	1.43	-0.25	-0.32	Step hazard
14	-7.02	1.33	1.32	-0.16	-0.36	Step hazard
		1.37	1.36	-0.17	-0.35	Step hazard
		1.45	1.44	-0.18	-0.32	Step hazard
15	-4.22	1.29	1.29	-0.09	-0.37	Step hazard
		1.37	1.36	-0.10	-0.36	Step hazard
		1.45	1.44	-0.11	-0.32	Step hazard
16	-1.41	1.33	1.32	-0.03	-0.36	Step hazard
		1.37	1.37	-0.03	-0.35	Step hazard
		1.41	1.41	-0.03	-0.34	Step hazard
17	1.40	1.37	1.37	0.03	-0.34	Step hazard
		1.41	1.41	0.03	-0.33	Step hazard
18	4.21	1.33	1.32	0.10	-0.36	Step hazard
		1.37	1.36	0.10	-0.35	Step hazard
		1.45	1.44	0.11	-0.32	Step hazard
19	7.02	1.29	1.28	0.16	-0.37	Step hazard
		1.37	1.36	0.17	-0.36	Step hazard
		1.45	1.44	0.18	-0.32	Step hazard
20	9.83	1.37	1.35	0.23	-0.34	Step hazard
		1.41	1.39	0.24	-0.33	Step hazard
21	12.64	1.33	1.29	0.29	-0.36	Step hazard
		1.41	1.37	0.31	-0.34	Step hazard
		1.38	1.33	0.41	-0.00	Step hazard
22	15.45	1.41	1.36	0.37	-0.34	Step hazard
23	18.26	N O	H A Z A R D S		C A T A L O G E D	
24	21.07	N O	H A Z A R D S		C A T A L O G E D	
25	23.88	N O	H A Z A R D S		C A T A L O G E D	
26	26.69	N O	H A Z A R D S		C A T A L O G E D	
27	29.50	N O	H A Z A R D S		C A T A L O G E D	
28	32.31	N O	H A Z A R D S		C A T A L O G E D	
29	35.12	N O	H A Z A R D S		C A T A L O G E D	
30	37.93	N O	H A Z A R D S		C A T A L O G E D	
31	40.74	N O	H A Z A R D S		C A T A L O G E D	
32	43.55	N O	H A Z A R D S		C A T A L O G E D	

Figure 23: Modeler program output with 30 cm high box as hazard.

Another situation, where the height of one of two adjacent boxes was varied, resulted in crosspath hazards about where expected, but a modeler program deficiency was uncovered for the following test case. Two 31 cm x 185 cm boxes high enough to be considered step hazards were placed parallel to each other about a meter from the mast. The spacing between them was varied from 100 to 150 cm to simulate a narrow pass through which the 135 cm wide rover must fit. The hazards on each side showed very well, but the path selection program has no algorithm to decide on the safety of such a situation from a distance.

Additional testing was performed on boxes at various ranges showing an effective range of about 230 cm, probably due to limited elevation angles. Small holes were detected when more than 30 cm deep, and larger ones at 25 cm. Some apparently anomalous results were probably due to multiple light reflections.

At the present time (1984) there are no funds available to continue work actively in implementing any new systems, but the test program is continuing with the involvement of several students and two faculty members.

V. CONCLUSION

Autonomous travel on another planet requires considerable engineering effort and often the introduction and verification of new concepts. Our efforts on this project began with the development of a vehicle that was capable of unfolding itself from a relatively small volume. An additional advantage of this flexibility was the capability of raising and lowering the payload height and even reversing the front and rear wheel pairs, to rescue the rover from every conceivable condition of entrapment. This vehicle also was equipped with very low weight, high traction, and non-pneumatic tires. The vision system was developed basically as an obstacle avoidance scheme that had little interest in anything outside of whether or not the terrain immediately inn front of the vehicle was safe. Unfortunately, the vision system mast prevents use of the deployment system initially developed.

The results from the 1978 indoor tests demonstrated that a relatively crude, low-resolution vision system scanned in one dimension, along with some simple avoidance algorithms, was sufficient to prevent collisions with walls, large boxes, etc. on a level surface. The outdoor tests showed that under artificial terrain conditions that would certainly block or upset the vehicle if unguided, the intelligent vehicle was able to find a safe but tortuous path in the general direction of the prescribed heading. The considerable time and effort expended since then on a two-dimensionally scanned vision system do result in considerable improvement in the quantity and quality of available information about the local terrain. Along with the many hardware and software improvements, the vehicle should be capable of even better performance in the same situations as for the 1978 tests. Actual vehicle tests using a MLMD mast have not yet been conducted, however.

Use of an off-board computer has been helpful in that all the data from a test run of the mast or vehicle can be stored digitally and analyzed later from any

point of view desired. Most of the algorithms for vehicle control are relatively simple, and there is no requirement for long term data storage, so a small computer on board the vehicle should be sufficient for all necessary processing in real time.

For actual use on a roving vehicle, the present MLMD system, with its many moving parts could lack sufficient reliability. Some interesting possiblities for a similar system lacking moving parts are described in Report MP-81 [28]. A less expensive system with no moving parts for the receiver, but a single lightweight rotating hologram diffraction grating as a laser beam deflector to replace the rotating mirror and mast is also discussed. Both these systems use cyclindrical lenses and a linear array of optical fibers connected to individual detector-amplifiers.

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